



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**WIRELESS ROBOTIC COMMUNICATIONS IN URBAN
ENVIRONMENTS:
ISSUES FOR THE FIRE SERVICE**

by

George Hough

March 2008

Thesis Advisor:
Second Reader:

Richard Bergin
Kate Remley

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 2008	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE Wireless Robotic Communications in Urban Environments: Issues for the Fire Service			5. FUNDING NUMBERS	
6. AUTHOR(S) George Hough				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) <p>Firefighters are tasked with conducting search and rescue operations at incidents ranging from minor smoke conditions to multi-agency disasters. In each instance, a rapid risk assessment must be conducted based on preliminary dispatch information. Small lightweight "man portable" robots are a natural fit for gaining improved situational awareness, yet few have been employed for this application. The problems encountered in using wireless robots in urban environments are among the primary reasons. This thesis focuses on the wireless link between the robot and the firefighter employing it. The work presented is useful for policy makers in allocating public safety spectrum, firefighters in pre-planning responses, and engineers for designing relevant control systems. While the arguments rest on a technical footing of test data and models, the paper is written primarily for a non-technical audience.</p> <p>A technology acceptance model is developed for employing robots wirelessly. Test data is presented showing the debilitating effects of interference from employing multiple robots concurrently. Models are applied to predict signal loss in tunnels and urban environments, and results indicate an optimal frequency range exists between 500 MHz and 1 GHz. A case is presented to allocate spectrum in this range using a priority access protocol.</p>				
14. SUBJECT TERMS Wireless, Robot, Communications, Fire, Search, Rescue, Urban Environment			15. NUMBER OF PAGES 169	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

**WIRELESS ROBOTIC COMMUNICATIONS IN URBAN ENVIRONMENTS:
ISSUES FOR THE FIRE SERVICE**

George C. Hough
Lieutenant, New York City Fire Department
B.S., Columbia University, 1988

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF ARTS IN SECURITY STUDIES
(HOMELAND SECURITY AND DEFENSE)**

from the

**NAVAL POSTGRADUATE SCHOOL
March 2008**

Author: George Hough

Approved by: Richard Bergin
Thesis Advisor

Kate Remley, Ph.D.
Second Reader

Harold A. Trinkunas, Ph.D.
Chairman, Department of National Security Affairs

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Firefighters are tasked with conducting search and rescue operations at incidents ranging from minor smoke conditions to multi-agency disasters. In each instance, a rapid risk assessment must be conducted based on preliminary dispatch information. Small, lightweight “man portable” robots are a natural fit for gaining improved situational awareness, yet few have been employed for this application. The problems encountered in using wireless robots in urban environments are among the primary reasons. This thesis focuses on the wireless link between the robot and the firefighter employing it. The work presented is useful for policy makers in allocating public safety spectrum, firefighters in pre-planning responses, and engineers for designing relevant control systems. While the arguments rest on a technical footing of test data and models, the paper is written primarily for a non-technical audience.

A technology acceptance model is developed for employing robots wirelessly. Test data is presented showing the debilitating effects of interference from employing multiple robots concurrently. Models are applied to predict signal loss in tunnels and urban environments, and results indicate an optimal frequency range exists between 500 MHz and 1 GHz. A case is presented to allocate spectrum in this range using a priority access protocol.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	PROBLEM STATEMENT	4
B.	RESEARCH QUESTION	6
C.	SIGNIFICANCE OF RESEARCH	7
D.	METHOD	9
II.	LITERATURE REVIEW	11
A.	EARLY MAN-PORTABLE ROBOT DEVELOPMENT EFFORTS	11
B.	IMPROVING FIREFIGHTER/RESPONDER SAFETY USING ROBOTS.....	13
C.	NEED FOR PUBLIC SAFETY COMMUNICATIONS AND ROBOTICS	15
D.	EXPLOSIVE ORDNANCE DISPOSAL (EOD)/MILITARY OPERATIONS IN URBAN TERRAIN (MOUT).....	17
E.	US&R ROBOTIC REQUIREMENTS	18
F.	EVIDENCE OF WIRELESS COMMUNICATIONS ISSUES IN SPECIFIC ENVIRONMENTS.....	20
G.	GENERAL COMMUNICATIONS ISSUES FACED BY FIREFIGHTERS	21
H.	EFFORTS TO ADDRESS PROBLEMS	22
I.	GAPS IN CURRENT LITERATURE	23
J.	SUMMARY	23
III.	METHODS AND DATA	25
A.	TECHNOLOGY ACCEPTANCE MODEL FOR ROBOTS	25
1.	Technology Acceptance and Reliability	25
2.	Application of Tactical Employment Categories to TAM.....	30
3.	Reliability of the System	31
4.	External Factors.....	32
B.	OPERATIONAL ENVIRONMENT – OPPORTUNITIES FOR EMPLOYMENT	36
1.	Transportation Emergencies – Terrorism and Accidents.....	36
2.	Chemical, Biological, Radiological, Nuclear, Explosive (CBRNE), and Hazardous Materials Emergencies.....	41
3.	Emergencies - Technical Rescue (Confined Space, Collapse) and Utilities.....	42
4.	Strategic Goals and Tactical Objectives	42
5.	Additional Considerations.....	44
C.	PHYSICAL ENVIRONMENT	45
1.	Free Space Path Gain (Loss).....	47
2.	When Radio Waves Collide: Transmission, Reflection, Scattering, Fading	48
3.	Flat Earth Path Gain	51

4.	Diffraction.....	54
5.	Tunnels.....	55
a.	<i>Small Tunnel – Cave, Mine, Utility Tunnel.....</i>	<i>58</i>
b.	<i>Medium Dimension Tunnel – Under River Subway and Automobile</i>	<i>62</i>
c.	<i>Massif Tunnel (France) Test Results.....</i>	<i>63</i>
d.	<i>Curvature in a Tunnel</i>	<i>64</i>
6.	Propagation in Urban Canyons	66
7.	Buildings: Communications Inside, Outside-to-Inside, and Around Structures	70
8.	Additional Factors	74
D.	RADIO ENVIRONMENT: CAPACITY, INTERFERENCE, AND PROTOCOLS	74
1.	Link Margin	74
2.	Capacity	77
3.	Protocol and Interference.....	84
a.	<i>External Interference Sources.....</i>	<i>86</i>
b.	<i>Confliction: Near Far Problem</i>	<i>86</i>
4.	Modulation Techniques.....	88
E.	EXTENDING THE RANGE OF ROBOT COMMUNICATIONS	90
IV.	SCENARIOS	93
A.	SCENARIO A: RAIL TANK CAR ACCIDENT WITH HAZARDOUS MATERIALS.....	94
1.	Hazardous Materials Release.....	94
2.	Strategic Responder Considerations	95
3.	Initial Actions	95
4.	Hazard Assessment	95
5.	Vulnerability Analysis	96
6.	Resource Assessment	96
7.	Risk Benefit Analysis	96
8.	Tactical Objectives for Employing a Robot.....	96
9.	Operating Range for Various Frequencies of Interest: Excess Link Margin	97
B.	SCENARIO B: EXPLOSION IN AN UNDER-RIVER SUBWAY TUNNEL.....	99
1.	Strategic Responder Considerations	99
2.	Initial Actions	100
3.	Hazard Assessment	100
4.	Vulnerability Analysis	100
5.	Resource Assessment	100
6.	Risk Benefit Analysis	101
7.	Tactical Objectives for Employing Robot.....	101
8.	Evaluating the Wireless Signal in the Tunnel	102
9.	Considerations for this Scenario.....	102

C.	SCENARIO C: RADIOLOGICAL EXPLOSION IN DOWNTOWN AREA	103
1.	Description of Scenario.....	103
2.	Strategic Responder Considerations	104
3.	Initial Actions	104
4.	Hazard Assessment	105
5.	Vulnerability Analysis	106
6.	Resource Assessment	106
7.	Risk Benefit Analysis	106
8.	Tactical Objectives of Employing Robot	106
9.	Evaluating the Wireless Signal in Urban Canyon RDD Explosion: Urban Canyon Model with Turn onto Side Street	107
10.	Considerations.....	109
D.	SCENARIO D: INTERFERENCE EFFECTS	111
V.	ANALYSIS OF RESULTS.....	117
A.	IMPLICATIONS OF MODELS AND STUDIES UPON FREQUENCY SELECTION.....	117
VI.	RECOMMENDATIONS AND CONCLUSION.....	123
A.	FUTURE RESEARCH OPPORTUNITIES FOR OPERATIONAL, TECHNICAL, AND REGULATORY STANDARDS.....	123
B.	OPPORTUNITY FOR A JOINT ROBOTICS EFFORT	126
APPENDIX A.	FORMULAS.....	129
APPENDIX B.	137
A.	BUILDING WALL LOSS.....	137
B.	BUILDING PENETRATION	138
APPENDIX C	139
LIST OF REFERENCES	141
INITIAL DISTRIBUTION LIST	151

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1.	Davis Technology Acceptance Model (TAM): $BI=A+U$	26
Figure 2.	Modified Technology Acceptance Model	32
Figure 3.	External Wireless Variables for TAM	34
Figure 4.	Radio Spectrum.....	46
Figure 5.	Fresnel Zone about the Transmitting and Receiving Antennas	47
Figure 6.	Freespace Path Gain vs. Distance for 50MHz to 4900MHz.....	48
Figure 7.	Standing Wave Pattern.....	49
Figure 8.	Two Ray Flat Earth Diagram.....	51
Figure 9.	Flat Earth Path Gain for 50 MHz to 4900 MHz.....	52
Figure 10.	Free Space vs. Flat Earth Path Gain 50 MHz to 4900 MHz	53
Figure 11.	Diffraction around a Corner.....	54
Figure 12.	Small Sized Tunnels ,	58
Figure 13.	Hazel Atlas Tunnel 448 MHz Path Gain: Measured Data vs. Theory.....	59
Figure 14.	Theoretical Path Gain for Rough Walled Tunnel	60
Figure 15.	Theoretical Path Gain for Smooth Walled Tunnel	61
Figure 16.	Subway Tunnels,.....	62
Figure 17.	Massif Tunnel Path Gain Measurements	63
Figure 18.	Theoretical Path Gain for Massif Tunnel.....	64
Figure 19.	Attenuation in a Tunnel with Curvature	65
Figure 20.	Urban Canyon Effect,	66
Figure 21.	Urban Canyon Path Gain	67
Figure 22.	Urban Canyon with Turn onto Side Street,.....	69
Figure 23.	Transmission through a Wall.....	71
Figure 24.	Propagation Paths and Path Loss between Floors of a Building	72
Figure 25.	Building Penetration Loss.....	73
Figure 26.	Wireless Transmission Link	75
Figure 27.	Excess Link Margin Equation.....	77
Figure 28.	Shannon's Channel Capacity Theorem.....	78
Figure 29.	Signal to Noise Ratio (SNR) From [96]	78
Figure 30.	Path Gain vs. Distance	80
Figure 31.	Excess Link Margin vs. Distance.....	80
Figure 32.	Shannon Capacity vs. Distance.....	81
Figure 33.	(a-d) – ELM and Shannon Capacity for 100 KHz, 1 MHz BW 33(a) to 33(d): beginning top left and moving clockwise	82
Figure 34.	802.11b 2.4 GHz Channels	85
Figure 35.	Bit Error Probabilities as a Function of Delay-Spread and SNR.....	89
Figure 36.	Throughput as a Function of Hops.....	91
Figure 37.	Hazardous Material Tank Car Accident	94
Figure 38.	Excess Link Margin for 50 MHz to 4900 MHz Signals	98
Figure 39.	Under River Subway Explosion.....	99
Figure 40.	Excess Link Margin for Tunnel with Curvature	102
Figure 41.	Radiological Dispersal Device (RDD) Explosion	103

Figure 42.	Urban Canyon with Turn (From Appendix A)	104
Figure 43.	Excess Link Margin	107
Figure 44.	Elevated Transmitter with Turn onto Side Street	108
Figure 45.	Path Gain Profiles for an Elevated Repeater Tx at 1.5m height (h) to Repeater at 20m (h) to Robot on a Side Street at 1m (h)	109
Figure 46.	NIST US&R Robot Test Event.....	111
Figure 47.	(a-c) - Signal Measurements	113
Figure 48.	Smooth Rectangular Tunnel: 4.5m x 3.3m, Flat Earth: h1=1.5m, h2=1.0m, Freespace.....	118
Figure 49.	Knife Edge Diffraction	130
Figure 50.	Curved Tunnel Path Loss.....	133
Figure 51.	Top View of Street Canyon	135
Figure 52.	Top View of an Urban Canyon with a Turn onto a Side Street.....	136
Figure 53.	Wall Path Loss	137
Figure 54.	Building Penetration Loss.....	138
Figure 55.	Media Independent Co Existence (MICE) Service Layer	139

LIST OF TABLES

Table 1.	Summary of Data Collected by NIST at the August 19-20, 2006 at the Montgomery County Fire Rescue Training Academy	115
Table 2.	Summary Table of Spectrum Availability for Public Safety	122

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

As most people that attend the CHDS program would agree, it is not possible without a good deal of support. I would like to begin by expressing my sincere gratitude for the opportunity to represent the NYC Fire Department in attending this program to Commissioner Nicholas Scopetta, 1st Deputy Commissioner Frank Cruthers, Chief of Department Salvatore Cassano, Chief of Operations Patrick McNally, AC Michael Weinlein, DAC Joseph Pfeifer, DAC William Siegel, DC Nicholas DelRe, and BC Frank Naglieri.

To my thesis advisor Richard Bergin for encouraging me to pursue this topic from the very beginning, and for guiding and ensuring that I stayed on track to the end. Thank you for all of your hard work and for putting me in touch with so many knowledgeable and helpful people at NPS. It was a tremendous experience.

I would like to thank Dr. Kate Remley of the National Institute of Standards and Technology for all that she has done to support my thesis. In addition to collecting test data in conjunction with the TNT-MIO experiments, you spent countless hours helping me to appreciate your important work at NIST on behalf of public safety. It was a fantastic and enjoyable learning experience.

A special thank you goes to Dr. Henry Bertoni, Professor Emeritus of Polytechnic University. While assisting me in navigating this complex field, I came to see the qualities that made him such an accomplished and valued instructor for 40 years. It was both an honor and a pleasure to venture down a few well chosen rabbit holes with you during the process.

A great deal of appreciation goes to Dr. Alex Bordetsky, Director of the NPS CENETIX lab and TNT-MIO exercises, for his support during the Black Diamond Mine tunnel measurements as a component of the March 2007 TNT-MIO exercise. It was a great experience to be a part of your cutting edge work. Thank you also to LCDR Mike Clement for providing me with a better understanding of the networking issues that were a focal point of his thesis, and for helping me to lay out mine in a more effective manner.

I would like to recognize in particular those members of the FDNY that provided assistance and support for my education and thesis:

AC Joseph Pfeifer, Chief of Counterterrorism and Emergency Preparedness, for the feedback that he provided to ensure that this paper meets with the future goals of the department in responding to terrorist events.

BC Robert Ingram, for the benefit of his extensive knowledge and experience in the field of hazardous materials response and for continued support all these years.

BC Richard Schlueck, for providing his expertise on aspects of this work that dealt with radiation.

BC John Esposito for reviewing my thesis and helping to ensure that the perspective provided is grounded in reality.

Captain John Flynn for his support and advice throughout my entire time in the program, and for providing me the benefit of his lessons learned in attending NPS.

To the officers and firefighters of Hazmat Company 1; thank you for your support and encouragement throughout my time in the program.

To the faculty, staff, and classmates of Cohort 0603/0604; the richness of the experience is brought about by the people that comprise the program, and it was an amazingly rich experience to say the least. Thank you for all that you have taught me.

To Greta Marlatt for her expert assistance in helping me to research this work and for graciously reviewing it on my behalf. To Kate Snider and Monique Cadoret for their edits and formatting.

Most importantly to my wife, Melissa, for her encouragement, patience, and support these long months. Simply, thank you for all the joy that you bring to my life.

This thesis is dedicated to all firefighters of the FDNY that have made the supreme sacrifice in the line of duty; and in particular to the 343 firefighters that gave their lives on 9/11/01. Never Forget.

I. INTRODUCTION

Without doubt, firefighting is a dangerous business. Firefighters are called upon to respond to incidents that range from relatively minor smoke conditions to multi-agency disasters. In each instance, a firefighter must perform a rapid risk assessment during the first critical minutes with relatively little initial dispatch information on the nature of the hazard. If an initial search is determined to be warranted, firefighters must also decide on the level of risk to assume in searching for someone who may be incapacitated in the affected area. In addition, firefighters must operate in a wide variety of environments that range from below-grade under-river tunnels to high-rise buildings. Recognizing these challenges, fire departments continually seek to raise the standard of care that they provide while concurrently enhancing the safety of their members. This is primarily accomplished through employing new equipment that allows responders to gain improved situational awareness and reduces their potential exposure when possible. Small, lightweight “man portable” robots would seem a natural fit for obtaining improved situational awareness in many response scenarios. Yet, few departments have begun to utilize robots to date.

Among the challenges that fire departments face in employing robots in urban environments is the wireless link that connects the operator to the robot. This thesis seeks to explore the issue by examining the problems and concerns that have been encountered thus far during actual responses as well as Department of Homeland Security (DHS) test events trying to operate robots wirelessly. While the argument presented is grounded in technical detail, the paper is written in such a way that all readers might appreciate the core issues without needing to delve into the minutia of wireless signal propagation. It is hoped that policy makers might better appreciate the implications of spectrum allocation; firefighters and other responders might find the explanations and models useful; and manufacturers and system designers might come to better appreciate the types of scenarios in which responders might employ robots.

The issue of incorporating robots into fire department search operations is relatively new. Robotic platforms have only recently reached a point of technological sophistication that justifies fire departments examining their potential to assist responders in severe operating environments. Most firefighters are relatively unaware of the capabilities that robots can offer. In an after-action report by the Navy's Space and Naval Warfare Systems Command (SPAWAR) agency following the efforts to employ robots at the 9/11/01 World Trade Center (WTC) response, the authors concluded that civilian emergency first responders have had little opportunity to work with robots in search and rescue operations, and are generally unaware of the potential applications of robot technology.¹ DHS has helped to improve the situation by bringing Urban Search and Rescue (US&R) members from many of the 28 national task forces together to develop performance-based standards to compare platforms, and in the process gain additional familiarity with the platforms in training scenarios as part of a National Institute of Standards and Technology (NIST)-managed standards development effort. One of the key concerns seen by responders at these test events has been the problems experienced in attempting to successfully teleoperate the platforms through the test courses. Issues of operating range and interference among multiple robots have been found to be a severely limiting factor, to the point where it remains questionable whether this technology might ever be suitable for many real world search and rescue missions – be it for US&R or fire service operations – unless communications are improved.

In order to utilize new equipment in challenging response environments, firefighters need to gain a level of confidence in the equipment that they employ. A key concern is whether the device is reliable and useful during the initial chaotic minutes of a response. Wireless communication is notably among the more challenging aspects of emergency response in urban environments, and wireless robotic operation adds an additional level of complexity due to the need to maintain both a video and control link. Although many of the technical aspects of the issue – signal propagation, capacity, and

¹ Michael R. Blackburn, H. R. Everett, and Robin T. Laird, After Action Report to the Unmanned Ground Vehicles/Systems-Joint Program Office: Center for the Robotic Assisted Search and Rescue (CRASAR) Related Efforts at the World Trade Center (San Diego, CA: SSC San Diego, 2002), Section 4.3, 13. <http://handle.dtic.mil/100.2/ADA407901> (Accessed March 1, 2008).

interference – are generally understood by academics and engineers, the problem in its entirety as it applies to emergency response bears further analysis.

While studies have been conducted on the use of robots for US&R, military operations in urban terrain (MOUT), and explosive ordinance disposal (EOD), the issue has not been explored in greater detail in literature covering tactical applications other than noting that wireless communications are a problem. Part of the goal of this thesis is to examine the issues involved with maintaining a wireless robotic link with an eye toward examining how an assortment of related factors may affect the reliability of a robotic device, and potentially the ultimate adoption of robotics for the fire service. This goal is in keeping with Homeland Security Presidential Directive 8 (HSPD-8), from which the *National Preparedness Guidelines* (NPG) has been derived. The NPG provides a vision by stating, “A nation prepared with coordinated capabilities to prevent, protect against, respond to, and recover from all hazards in a way that balances risk with resources and need.”² The NPG addresses all hazards, but places heavy emphasis on catastrophic events such as terrorist attacks that would require a rapid and coordinated national action. A companion document – *The Target Capabilities List* - is considered a “living document” that defines 37 specific capabilities that stakeholders should possess to effectively respond to disasters based on the 15 National Planning Scenarios. Among the response mission capabilities listed in the NPG, wireless ground-based robotics holds the potential to support aspects of the following:

- Responder Health and Safety
- Fire Incident Response Support
- WMD/Hazardous Materials Response and Decontamination
- Search and Rescue (Land-Based)
- Explosive Device Response Operations

While the focus of this thesis is to support an urban fire department response using robots during the critical initial minutes of an incident, many of the wireless

² US Department of Homeland Security, *National Preparedness Guidelines* (Washington, DC: US Department of Homeland Security, 2007), 1. <https://www.hsd1.org/homesecc/docs/dhs/nps23-091407-01.pdf&code=d3fb737cee88df0f3c62d3d65e80f479> (Accessed March 1, 2008).

considerations presented are applicable to other areas of robotics interest. An additional goal of this thesis is to further the common mission target capability of communications by exploring interoperability problems that were exposed during the employment of multiple robots at a DHS-sponsored US&R robotics test event.

A. PROBLEM STATEMENT

The field of robotics holds the promise of assisting emergency responders in performing their mission of search and rescue in a way that is both safer and more efficient than exists today. Currently, very few urban fire departments employ robots to gain increased situational awareness in the first critical minutes of a response. By contrast, a significant amount of interest exists in the academic world, as evidenced by worldwide search and rescue robotics contests and conferences held annually. While robot platforms have shown marked progress -- due in large part to substantial investment in research and development by the military -- the wireless communication link between the operator and robot remains a key barrier to technology adoption, especially given that this component may serve as the lynchpin in determining the viability of utilizing wireless robotic platforms during response operations. The usefulness of robotics to the fire service hinges upon both the reliability of the system and on the perceived reliability by the operator. A robot must be able to return useful information in a timely manner when employed. The operator must also understand the capabilities and limitations of the system with respect to the surrounding environment. While this may seem intuitive when considering whether to use one robotic platform compared to another based on size and mobility, determining the suitability of a particular wireless system is not as straightforward.

Pre-planning an incident is part of preparedness for the fire service. Plans are generalized representations of the way a response is intended to be managed. Academia also develops models to predict performance of systems and then seeks to validate the models through testing. A conjoined approach -- of testing a wireless system in an environment -- and comparing the results with what would be anticipated from a model is useful to better appreciate whether future missions can be accomplished, whether the

system is functioning properly, and whether the model needs to be adjusted. By examining relevant wireless propagation models for specific physical environments, the goal is to better understand the interrelationship of the physical, operational and radio environments.

In addition, many of the wireless difficulties that have been experienced in responses and test events should be viewed as more than a communications problem that might be solved with minor modification to existing equipment. An effective solution will require thought on the best way agencies might share limited spectrum, along with a discussion of how agencies may operate without conflicting with each other. In order to gain an adequate understanding of the barriers to improved reliability and perceived usefulness, one must first look at the mission requirements, operating environment, and physical constraints.

Although case history of robots being employed for search and rescue at disaster sites is limited, useful information was captured following the September 11, 2001 attack on the World Trade Center. During the rescue effort, a cache of robots were brought to the site to assist with searching voids. Some of the problems encountered in this relatively extreme radio environment included the limited range of signal transmission due to the substantial amount of twisted metal and small voids. In one area of the complex, control over one robot that was a mere 30 feet into a collapsed structure was completely lost.³ Operating environments more routinely encountered in fire department operations – such as subway tunnels and urban canyons – also degrade the quality of signal transmissions, but in a somewhat more predictable manner, as will be seen in Chapter III.

The issues involved in discussing robot communications go beyond multi-path and signal attenuation to involve a discussion of available spectrum to meet capacity requirements, as well as coordination amongst responders in order to avoid wireless interference. As part of the DHS-sponsored project to develop standards for robots to be used by US&R teams, NIST has confirmed through testing that operators trying to

³ Robin Murphy, “Rats, Robots, and Rescue,” *IEEE Intelligent Systems* 17, no. 5 (September/October 2002): 8.
<http://csdl2.computer.org/persagen/DLAbsToc.jsp?resourcePath=/dl/mags/ex/&toc=comp/mags/ex/2002/05/x5toc.xml&DOI=10.1109/MIS.2002.1039826> (Accessed June 2, 2007).

wirelessly control multiple robots in the same area at the same time create interference problems.⁴ The interference issues are due in part to the frequency and protocol that are commonly used to transmit large bandwidth video signals. Currently, civilian agencies have few choices that would allow them to employ multiple wireless broadband devices – not only robots – at a future disaster scene while avoiding the interference that can be created amongst these devices.

B. RESEARCH QUESTION

Based on the aforementioned considerations, the following research questions bear examination:

- Technology Acceptance: How does perceived reliability factor into perceived usefulness of a new technology such as robotics, and thereby affect a responder's attitude and intent to utilize a robot?
- Operational Environment: In which operating environments and tactical situations are robots likely to be found useful to firefighters? What strategic benefits might be gained by an increased situational awareness – along with a corresponding improvement in responder safety – in these environments given the constraints of wireless communications?
- Physical Environment: How do challenging operating environments affect signal propagation? Do some frequencies perform better than others in specific settings?
- Radio Environment: How much impact might interference from other operating devices have on current wireless robotics systems, and what options are available to address this problem? What are the important characteristics of a system that will support a multi-agency response effort?

⁴ Kate A. Remley and others, "Standards Development for Wireless Communications for Urban Search and Rescue Robots" (*Proceedings of the International Symposium on Advanced Radio Technologies* Boulder, CO, 2007), 66. http://www.nist.gov/public_affairs/techbeat/NISTRobotCommStds1.pdf (Accessed March 4, 2007).

- Spectrum and Standards: Given the operating environments considered, what spectrum would be most desirable? What aspects of an operating protocol are important?

Based on the answers to these questions, what are the implications for development of new equipment and protocols to meet the determined needs? How would this affect spectrum policy for public safety?

C. SIGNIFICANCE OF RESEARCH

In looking at the issue of wireless use of robotics from a holistic standpoint that includes operational requirements, signal propagation, and link margin for a few common response scenarios, the importance of the sum of these issues will be considered. In addition, conclusions will be drawn for future policy considerations with respect to spectrum and protocols to support robot use. Understanding these options will set the stage for further research, development and discussion of the steps that are needed to enable more effective use of robots by responders. The conclusions that are derived from this study may benefit more than the wireless control of robots, as wireless video cameras, laptops, and metering devices all vie for the same airspace at a disaster site, and need to be coordinated.

Taking time to examine these issues in order to develop solutions is worthy of consideration, and the greatest benefit may be seen in allowing robots to become more widely adopted for firefighting and search and rescue. Concurrently, looking at the problem space may also offer possible explanations why robots have not been more widely utilized to the present. Although the following discussion focuses on the fire service, many aspects of this paper may prove useful to the ASTM (originally known as American Society for Testing and Materials) standards and performance metrics development effort - ASTM E54.08.01: Robots for Urban Search and Rescue. The topic of wireless transmission of video and data is also particularly relevant for the current focus by DHS on responder communications – wireless control of robots being a lesser known, but important, subset of this topic.

In the process of looking at issues that may affect reliability and usefulness of robots, the discussion will consider end-user acceptance for incorporating technology that provides better information (video, sensor data, etc.) while reducing uncertainty. Improved situational awareness facilitates better decision making concerning whether to enter enclosed areas that may present chemical or radiological hazards. This knowledge translates into better risk management at a disaster, which provides a strategic advantage for all responders at the event. The strategic benefit of a responder remaining part of the solution, rather than becoming part of the problem, is enormously important – not only for the safety of that individual, but also for an incident commander leveraging the full operational capabilities of an agency’s assets for protecting the public. At minimum, a better appreciation for the limitations that might be expected upon trying to employ robots at an emergency should be useful to agencies that may be considering the purchase of robots.

Some may challenge the importance of the issues discussed so far by questioning whether wireless operation is important in the first place. They may point to the fact that explosive ordinance disposal (EOD) units employ robots in challenging environments and can accomplish their mission either wirelessly or tethered even if communications break down. To this point I would argue that tethered operation of robots would negatively impact many fire service response missions where operational delays caused by equipment setup and cable entanglement on debris may cost responders precious minutes for locating victims. While tethered operation is useful in some circumstances and may allow for the retrieval of smaller platforms in smaller spaces via a durable cable, the applications discussed in this paper will necessitate platforms that are larger and are required to traverse greater distances over rough terrain that would effectively negate use of tethers.

Another argument against investing time and effort into addressing wireless issues suggests that since few robots are utilized currently, it is not worth devoting time and expense toward developing new operating protocols and allocating precious spectrum towards fixing the interference problems encountered at the test events. While it is accurate that few robots are currently used and it remains to be determined how prevalent

these devices become, this argument is somewhat shortsighted. Until responders begin to apply robots to real situations, they will not truly begin to find new and innovative ways that would lead them to incorporate robots into their standard operating procedures. Yet, without providing more effective communication alternatives, responders' efforts to employ robots will most likely fall short of justifying further time and effort in pursuing this technology. Maintaining the status quo becomes a self-fulfilling prophecy that robots will never be significantly utilized. An additional consideration is that the time and effort employed in finding better communications for robots will also apply to improving the wireless use of video cameras, laptops and telemetry equipment. The importance of this may only be fully realized as the use of wireless devices increases during response operations, and/or the next major multi-agency disaster response takes place.

Finally, to an incident commander that has sent firefighters down a tunnel without much knowledge behind the cause of the emergency or secondary hazards that may be present, the idea of sending a non-human device to perform reconnaissance should be appealing. The information gained may allow the responders to take the proper precautions before following the robot into potentially contaminated areas. Shedding light on the subject may influence development efforts by manufacturers to produce equipment that enhances a coordinated response. The solutions generated may also benefit other unforeseen civilian robot applications in the home and workplace, two potentially enormous future markets.

D. METHOD

The focus of this thesis begins in Chapter II with a review of literature that cites the call for increased use of robots. Some of the wireless problems that have been documented in using robots during training and responses will be presented. Use of robots for US&R, EOD, MOUT, and other applications will be discussed.

In Chapter III, the link between prior technology acceptance models will be considered with regard to a long term study of robots for a Swedish MOUT unit. The conclusions will be used as a basis for proposing a new technology acceptance model for

using robots in the fire service. The wireless control link will be considered as a precursor for determining ultimate perceived usefulness of robots in this application. The link between the physical, operational, and radio environments will be explored in depth based on response procedures, propagation models, and test data.

This will set the stage for examining how the propagation models from Chapter III apply to specific situations in Chapter IV by considering three response scenarios with respect to the use of robotics: hazardous materials release from a rail tank car, explosion in a subway tunnel, and a radiological dissemination device in a downtown urban area. Along with a discussion of the operational requirements of responders at each scenario, the radio frequency environment for each will be examined. Link budget calculations will be performed to assess potential operating ranges. Data from a NIST/US&R robotics test event will be examined for the interference effects of multiple robots operating at the same time. In Chapter V, implications for spectrum requirements will be drawn from the study. Results will be analyzed and options for addressing the issues will be presented.

Finally, in Chapter VI the current spectrum options will be discussed as they affect public safety use of robots. Recommendations will be made for peer-to-peer use of a new public safety band while utilizing new access protocols so that agencies that arrive ad hoc may be able to operate jointly on the same frequency. Mechanisms for achieving network coordination will be reviewed. Finally, additional options for spectrum use will be presented for future consideration. The overall intent is to present the interrelationship among technology, operations, standards, and spectrum that contribute to the reliability and perceived usefulness of a wireless robotic system, thereby opening the door to wider acceptance by the fire response community.

II. LITERATURE REVIEW

While a significant amount of literature exists concerning public safety wireless communication, relatively little exists that specifically addresses the eclectic mix of topics that play a role in adequately examining wireless robot control for fire service response. This is partly because the field is relatively new, and many of the issues are only coming to light as a result of recent testing and evaluation. This section will begin by providing background on early development efforts of small mobile robots for the U.S. military's Special Forces. US&R, EOD, and bomb squad use will also be examined, along with a case study of Swedish MOUT training operations. Current trends and future research and development will also be mentioned. Consideration will be given to applications most closely aligned with fire department response, along with the issue of whether current communications are adequate for response work.

Next, literature detailing a robot's potential utility for increasing responder safety will be explored as it will justify further work in this field. Recent work such as US&R requirements for utilizing robots and concurrent standards development work will be considered as a basis for discussion of what is required in order to employ robots effectively. Overall communication challenges that have been reported in a variety of literature will be covered, including some work detailing the use of robots during the response to the WTC on 9-11-2001. Data collected through NIST collapsed building tests on radio signal propagation will also be explored. Finally, literature describing efforts to address communication problems and detailing gaps in current knowledge will prove useful to set the stage for recommendations for future work in this field.

A. EARLY MAN-PORTABLE ROBOT DEVELOPMENT EFFORTS

In the middle 1990s, DARPA recognized the need for military Special Forces' use of robotics for their unique missions. They created the Tactical Mobile Robot (TMR) program in 1997 to identify critical robot employment scenarios for the military in the coming years, particularly in urban environments. The concept of utilizing smaller robots, also known as Man Mobile Robotic Vehicles (MMRVs), differed significantly

from prior military robotics efforts, which focused on large unmanned vehicles. The MMRV concept strove to utilize robots that could augment human capabilities rather than completely supplant them. Through taking this approach, rapidly deployable and logistically simple devices could be adapted to a variety of situations, rather than custom-making a larger robot for each specific application.⁵

A few significant advances in robot technology have materialized from the TMR program. Urbie, short for urban robot, was created out of a joint effort by the Defense Advanced Research Projects Agency (DARPA), NASA Jet Propulsion Laboratory (JPL), iRobot®, Inc., University of Southern California (USC) Robotics Research Laboratory, and the Carnegie Mellon University (CMU) Robotics Institute. Urbie's developmental progress was impressive, and as a result iRobot® was made lead systems integrator to develop its successor - Packbot®. In July 2002, Packbot® deployed to Afghanistan, where U.S. soldiers employed it in clearing caves and bunkers, searching buildings, and crossing live anti-personnel mine fields.⁶

Having recognized the success of the first generation of robots that emerged from the early DARPA program, the military is currently sponsoring a significant amount of development in the area of land mobile robots. This includes improvements in robot capabilities for searching caves, clearing buildings, and inspecting improvised explosive devices (IED). According to retired Navy Vice Adm. Joe Dyer, executive vice president and general manager of iRobot® Government & Industrial Robots division in Arlington, VA, "iRobot has a \$51.4 million contract to develop the Future Combat System (FCS) Small Unmanned Ground Vehicle (SUGV), a smaller, lighter successor to the combat-proven, man-portable PackBot. The FCS SUGV will be a portable, reconnaissance, and tactical robot that can enter and secure areas that are difficult to access or too dangerous

⁵ John Blitch, "Semi-Autonomous Tactical Robots for Urban Operations" (*Proceedings of the 1998 IEEE ISIC/CIRA/ISAS Joint Conference*, Gaithersburg, MD, September 14-17), 784.

⁶ NASA Center for AeroSpace Information *All-Terrain Intelligent Robot Braves Battlefield to Save Lives* (Washington, DC: NASA, 2007). http://www.sti.nasa.gov/tto/Spinoff2005/ps_1.html (Accessed June 2, 2007).

for humans.”⁷ Recently, iRobot® was also awarded a \$286 million Indefinite-Delivery/Indefinite-Quantity (IDIQ) contract from the U.S. Army Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI), on behalf of the Robotic Systems Joint Project Office at Redstone Arsenal, Alabama, to deliver up to 3,000 of the company's Packbot® military robot platforms over the next five years.⁸

The military and law enforcement communities have also utilized robots extensively for the task of explosive ordnance disposal. Presently there are approximately 550 bomb disposal units employing robots in their missions.⁹ In 1997, Congress funded the National Institute of Justice (NIJ) to provide state and local law enforcement agencies with better tools to combat terrorism. By surveying local law enforcement agencies, NIJ supported the creation of the report “Inventory of State and Local Law Enforcement Technology Needs to Combat Terrorism,” which listed improved robots for disarming and disabling explosive devices as its sixth highest priority.¹⁰

B. IMPROVING FIREFIGHTER/RESPONDER SAFETY USING ROBOTS

In examining areas where technology might benefit responders performing search and rescue, the Rand Corporation and the National Institute of Occupational Health and Safety (NIOSH) held a meeting of responders in New York City in December 2001 to assess responder safety needs when confronted with catastrophic natural or terrorist incidents. The project generated four reports; the third report, issued in 2006, recommended that:

⁷ John McHale, “Robots are Fearless,” *Military & Aerospace Electronics*, (June 2006). http://mae.pennnet.com/display_article/258264/32/ARTCL/none/none/1/Robots-are-fearless/ (Accessed June 2, 2007).

⁸ “iRobot Wins \$286 Million Army Robot Contract” HSDaily Wire.com, (December 19, 2007) <http://hsdailywire.com/single.php?id=5258>. (Accessed March 26, 2008).

⁹ “Building a Better Bomb Robot,” *TECH Beat*, e-Newsletter (Summer 2004). <http://www.nlectc.org/techbeat/summer2004/04-Building%20A%20Robot.pdf> (Accessed June 2, 2007).

¹⁰ James Wong, et al., *Urban Search and Rescue Technology Needs: Identification of Needs*, (Washington, DC: Department of Homeland Security and FEMA, 2004), 49. <http://www.ncjrs.org/pdffiles1/nij/grants/207771.pdf> (Accessed March 7, 2008).

...pilot projects and valuation efforts are also needed to validate the potential for changes in management processes or the application of new technologies to improve responder safety management.¹¹

Among the recommendations were “long-term, potentially high-payoff safety implementation opportunities” involving new technology that would improve hazard monitoring technologies and assessment aids.¹² Although not specifically mentioned, robotic development and technology transfer could be interpreted as fulfilling the spirit of this recommendation for improving responder safety.

While ample literature exists that supports the need to improve safety for emergency responders at incidents by incorporating new technologies, a relatively modest amount of literature exists that discusses the strategic benefits of employing robots to reduce responder uncertainty and risk during the initial stage of a catastrophic incident. A 2004 NIST-sponsored study analyzed the economic cost of firefighter injuries and saw a benefit in furthering research in robotic technologies, but did not outline the specific manner in which robots should be employed to improve safety. TriData Corporation, under contract with NIST, produced the study report titled, “The Economic Consequences of Firefighter Injuries and Their Prevention.” Robotics was mentioned, along with the numerous recommendations for improving firefighter safety, with the following statement:

Use of Robotics – The Japanese, Chinese and other nations are increasingly looking to robotics to reduce risks to firefighters. The United States has done little research in this area for firefighting, in contrast to our military, which is thinking in terms of increasing safety of soldiers by use of surveillance drones, tracked robots, and other means to do reconnaissance and even actual fighting.¹³

¹¹ Brian A. Jackson and others, *Protecting Emergency Responders, Volume 3 – Safety Management in Disaster and Terrorism Response* (Washington, DC: Science and Technology Policy Institute (RAND) and the National Institute for Occupational Safety and Health, 2004), Summary xxiii. http://www.rand.org/pubs/monographs/2004/RAND_MG170.pdf (Accessed June 2, 2007).

¹² Ibid., 92.

¹³ National Institute of Standards and Technology, *The Economic Consequences of Firefighter Injuries and Their Prevention - Final Report*, NIST GCR 05-874 (Washington, DC: National Institute of Standards and Technology, 2005), 42. http://www.fire.gov/newsletter/winter2005/Tridata/EcCostFFInj_GCR%2005_874.pdf (Accessed June 2, 2007).

A noteworthy study that specifically looked at the applicability of robots for transit emergencies details the potential for providing varied sensing capabilities for WMD-type events. However, it too only provides general guidance as to tactical use and wireless problems that may be encountered in transportation responses. The report sponsored by the Transit Cooperative Research Program – “Public Transportation Security: Volume 3 Robotic Devices: A Guide for the Transit Environment” – provides useful specifications for physical mobility requirements. Although it lists manufacturer-specified operating ranges – which vary widely from 0.4 to 2.2 miles – it provides only a short paragraph on the challenges likely to be encountered with robotic communications, stating, “How well a robotic device can be operated remotely depends on the radio environment in which it is used.”¹⁴

The Jet Propulsion Laboratory conducted a requirements assessment for robots to be used for search and reconnaissance in response to hazardous materials events in a laboratory environment. While the conclusions are useful for determining mobility and sensing needs for robots for fire service in this area, the system used was tethered, and also did not consider wireless use beyond looking at the pros and cons of each medium while noting that the addition of tetherless operation to allow vehicle deployment at distances greater than 100m from the incident site was desired.¹⁵

C. NEED FOR PUBLIC SAFETY COMMUNICATIONS AND ROBOTICS

DHS SAFECOM issued a Volume 2 Statement of Requirements (SoR) for wireless video and data to be used by public safety. Section 3.1 - Mission-Critical Video Services - includes applications in tactical public safety situations involving a potential risk to human life (i.e., either to the lives of the first responders or to the individuals the first responders are assisting). Along with ground- and air-based video and thermal

¹⁴ David M. Rose, *Public Transportation Security: Volume 3 - Robotic Devices: A Guide for the Transit Environment*, TCRP-86, (Washington, DC: Transportation Research Board, Transit Cooperative Research Program, 2003), 18, Table 2. http://trb.org/publications/tcrp/tcrp_rpt_86-v3.pdf (Accessed March 26, 2008), http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_86-v3.pdf (Accessed June 2, 2007).

¹⁵ R.V. Welch and G.O. Edmonds, *Requirements for Robots Utilized at HAZMAT Incident Sites* (Pasadena, CA: Jet Propulsion Laboratory/California Institute of Technology), 7. <http://hdl.handle.net/2014/33146> (Accessed March 1, 2008).

imaging infrared, it lists as a requirement robotic video at an emergency site to control robotic devices and to assist with tactical decision making by the incident commander.¹⁶

An international partnership of European Telecommunications Standards Institute (ETSI) and Telecommunications Industry Association (TIA) – Project MESA – produces technical specifications applicable for digital mobile broadband technology for public safety and disaster response, and provides a comprehensive set of requirements for many future emergency response technologies, including robots. It states that it envisions

...wireless robotic devices capable of moving into areas containing hazardous materials, chemicals, or explosive devices. It is anticipated that the robotic devices will be capable of performing a number of specific functions, including sending back video of where it is going and the obstacles it faces. More importantly, it is expected that these devices will be capable of being remotely controlled with regard to direction, moving around or over obstacles, performing complex manual tasks, analyzing specific chemicals or odors, and lifting or moving objects as commended.¹⁷

It further states that the standards specifications should allow for a 1,000-foot range between controller and robot, including the capabilities necessary to “penetrate difficult communications environments such as tunnels, mine shafts, fallen buildings, intense heat extreme cold, adverse weather and environmental conditions, and other potential search and rescue locations that are not conducive to normal commutations.”¹⁸ In Section A.28 – The use of robotics in a hazardous materials environment – the document goes on to state that the devices require full-motion video that can be transmitted over a distance of 1,000 meters. Equipment should be appropriate for operating in explosive atmospheres, and it “should not interfere with any approved device

¹⁶ The SAFECOM Program Department of Homeland Security, *Public Safety Statement of Requirements for Communications and Interoperability*, (August 18, 2006, Vol. 2, Version 1.0.) 13. http://www.safecomprogram.gov/NR/rdonlyres/B20DC842-B760-4DB0-B3B6-D3F1B0A5F26B/0/PS_SoR2_v10_9112006.pdf (Accessed March 4, 2008).

¹⁷ “What can Project MESA do for Public Protection, Public Safety, National Defense Organizations, and the Citizens They Serve,” <http://www.projectmesa.org/you/home.htm> (Accessed March 4, 2008).

¹⁸ Project MESA; Service Specification Group - Services and Applications; Statement of Requirements TS 70.001, (2005-01) Vol. 3.1.2, Section 8.15, 44. http://www.projectmesa.org/ftp/Specifications/MESA_70.001_V3.1.2_SoR.doc (Accessed February 9, 2008).

at all, explosive or otherwise.” It concludes by stating that the Project MESA SoR wireless data connectivity requirements will be vital to the operation of this equipment.¹⁹

D. EXPLOSIVE ORDNANCE DISPOSAL (EOD)/MILITARY OPERATIONS IN URBAN TERRAIN (MOUT)

While NIJ identified improved robotics specific to law enforcement needs, it is important to note that search and rescue task requirements are substantially different, leading to differences in requirements for robots. The very nature of bomb disposal work differs significantly from search and rescue work with respect to the pace, scale, and goals of the incident response. A search and rescue set of task requirements more closely resembles that of a military Special Operation Force (SOF) mission with respect to the rapid nature of the mission.

In 2006 a joint Swedish initiative involving the Royal Institute of Technology (KTH), the National Defense College (FHS), the Swedish Defense Materiel Administration (FMV), and the Royal Life Guards (LG) of the Swedish Armed Forces was conducted for assessing tactical robot use. An infantry company, specialized in Military Operations in Urban Terrain (MOUT), constituted the user group for the six-month study involving use of an iRobot® Packbot® Scout on their training maneuvers. It is interesting to note that soldiers indicated that the main technical drawbacks were the narrow field of view, poor image quality, and limited radio range. The authors concluded that the “capacity and range of the radio link greatly affects the usefulness of the robot system.”²⁰ One of the authors, Carl Lundberg, included additional details of this study as part of his doctoral dissertation, while also considering tactical police and firefighting use of robots among high risk professions in urban settings.²¹ His discussion with the fire service was limited to that of a specialty robot designed to deal with acetylene tank

¹⁹ “What Can Project MESA Do for Public Protection, Public Safety, National Defense Organizations, and the Citizens They Serve,” <http://www.projectmesa.org/you/home.htm> (Accessed March 4, 2008).

²⁰ Carl Lundberg, Henrik Christensen, and Roger Reinhold, “Long-Term Study of a Portable Field Robot in Urban Terrain,” *Journal of Field Robotics* 24, no. 8/9, (August 2007): 625.

²¹ Carl Lundberg, *Assessment and Evaluation of Man-portable Robots for High-risk Professions in Urban Settings*, PhD Dissertation, (Stockholm University, 2007) 111. <http://www.diva-portal.org/kth/theses/abstract.xsql?dbid=4540> (Accessed February 9, 2008).

emergencies, and did not focus on using robots for tactical firefighting search applications. The Swedish MOUT study does present an interesting case study for consideration in Chapter III regarding the acceptance of new technology among tactical users in a team setting.

E. US&R ROBOTIC REQUIREMENTS

The degree to which US&R work differs from SOF missions is significant enough to warrant its own set of robotic requirements. The Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA), and NIJ co-sponsored an effort to identify and define functional requirements for new and/or improved technologies that meet the needs of US&R teams. The high priority needs included:

reliable non-human, non-canine search and rescue systems - robust systems that combine enhanced canine/human search and rescue capabilities without existing weaknesses (i.e., robots).²²

Another noteworthy report is “Project Responder: National Technology Plan for Emergency Response to Catastrophic Terrorism” and was sponsored by DHS and the National Memorial Institute for the Prevention of Terrorism. In several places it mentions robots being potentially useful to responders, but states that the technology needs to be further developed, and specific requirements must first be defined. For example:

Sensor suite for robotics is a question of requirements, packaging and cost; not engineering...Requirements need to be generated to match the responder mission (weight constraints, power, endurance, standards, etc.).²³

The nature of emergency response is one that covers a wide variety of potential scenarios from building collapses to earthquakes to terrorist employment of WMDs. In

²² Elena Messina, et al, *Statement of Requirements for Urban Search and Rescue Robot Performance Standard: Preliminary Report* (Washington, DC: National Institute of Standards and Technology, 2005), 4. [http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements%20Report%20\(prelim\).pdf](http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements%20Report%20(prelim).pdf) (Accessed June 12, 2007).

²³ Ibid.

order to look more closely at the need to match responder requirements to robot capabilities, the DHS Science and Technology (S&T) Directorate initiated an effort in fiscal year 2004, with NIST, to develop comprehensive standards to support development, testing, and certification of effective robotic technologies for US&R applications. From their initial efforts, the NIST/US&R Responder consortium was able to define over 100 initial performance requirements, and generate 13 deployment categories. The performance requirements were grouped into categories such as human-system interaction, mobility, logistics, sensing, power, and communications. For each requirement, the responders defined how they would measure performance.²⁴

Through assisting in the process of creating such standards, DHS seeks to provide guidance to local, state, and federal homeland security organizations regarding the purchase, deployment, and use of robotic systems for US&R applications.²⁵ NIST has since organized the standards effort through ASTM E54.08 – Homeland Security Standards. In this effort, industry representatives and US&R responders have endeavored to slice the problem into manageable categories. The head of each working-group is responsible for producing his or her standard test method that objectively measures a robot's performance in a particular area. The goal is to provide a response organization with the ability to determine which robots best suit their requirements, similar to the way consumers select products such as cars and televisions based on published third-party test results. Robot researchers and manufacturers will benefit from the definition of test methods and operational criteria, enabling them to provide innovative solutions to meet universal requirements.²⁶ Since this is uncharted territory to a certain degree, questions remain as to which tactical applications end users will find most beneficial and whether they will ultimately perceive the technology as reliable. In addition, it remains to be seen how the firefighting response community might leverage the standards that are most pertinent for its daily response mission.

²⁴ Messina, et al, Statement of Requirements for Urban Search and Rescue Robot Performance Standard: Preliminary Report (Washington, DC: National Institute of Standards and Technology, 2005), 4.

²⁵ Ibid., 5.

²⁶ Ibid.

F. EVIDENCE OF WIRELESS COMMUNICATIONS ISSUES IN SPECIFIC ENVIRONMENTS

Instances of actual robot employment for search and rescue at a major disaster are relatively limited. A good deal of information was captured from the experiences of deploying robots at the World Trade Center attack on September 11, 2001. Many of the same robots that are currently used in Afghanistan and Iraq were employed previously at the WTC site – largely due to LTC John Blitch, who spearheaded an effort to utilize robots in an attempt to aid in searching for victims and assessing structural damage. He coordinated the efforts of academics, industry personnel, and military in the first known employment of robots at an actual disaster.²⁷

The rubble pile that the WTC collapse created was an extremely challenging, and in some ways unique, operating environment. The collapse impacted the building floors to such a great extent that relatively few voids were available to easily search – by either humans or robots. With that said, the robots that were employed did have some degree of success. Among these included Urbie. In an after-action report, it was noted that Urbie traversed an average distance of about 200 feet, and by “using digital RF communications did not encounter problems for the range and other conditions of deployment.”²⁸ Other robots employed at the site were not as successful. One of the academic robot teams that deployed to the WTC lost communication with a Foster Miller robot known as Solem - a recently declassified military robot prototype and forerunner to their TALON[®] robot. According to Dr. Robin Murphy,

The robot was operating in the area formerly known as WTC 4 when it lost communications less than 30 feet away under the pile. The radio wave physics and the density of the steel encountered made reestablishing the link impossible. It’s frustrating, but it’s reality. We’re working on ways to minimize the problem, but we can’t reinvent physics, and nobody has found a true solution yet.²⁹

²⁷ Robin R. Murphy, “Trial by Fire,” *IEEE Robotics & Automation Magazine* 11, no. 3 (September 2004): 50.

²⁸ Jennifer Casper and Robin R. Murphy, “Human–Robot Interactions during the Robot-Assisted Urban Search and Rescue Response at the World Trade Center,” *IEEE Transactions on Systems, Man, and Cybernetics, Part B, Cybernetics* 33, no. 3 (June 2003): 367.

²⁹ Robin R. Murphy, “Rats, Robots, and Rescue,” *IEEE Intelligent Systems* 17, no. 5 (September/October 2002), 8.

During the DHS/FEMA US&R/NIST standards project phase that entailed testing robots against various configurations of purposefully designed test-beds (i.e., standardized obstacle courses), a significant number of communication-related problems were encountered. Commercially available robots were put through a series of actual US&R training scenarios, with responders operating the robots at facilities in Nevada, Texas, and Maryland. During the testing done in Texas and Maryland, wireless communications were found to be problematic. At the August 2006 Maryland exercise, Dr. Kate Remley and Galen Koepke of the Electromagnetics Division of NIST developed and carried out a uniform series of spectral analysis tests on fourteen of the robots that participated in the event. The results of the testing data indicated that significant interference issues were created by the robots that were operating in the nearby vicinity during the trials.³⁰ Results will be presented in Chapter IV of this thesis.

G. GENERAL COMMUNICATIONS ISSUES FACED BY FIREFIGHTERS

A NIOSH-funded report that analyzed gaps in a firefighter's ability to communicate at incidents provides a broad overview of the issues involved – those of frequency, bandwidth, and path loss. The report's intent was to discuss the general issues that limit communications for firefighters in urban settings, without getting into specific scenarios. Robot communication was not included in the scope of the report.³¹

Over the last few years, the Electromagnetics Division of NIST has contributed to the knowledge base by conducting a series of spectral analysis measurements in a variety of settings that responders encounter, including a series of tests on three large structures that were imploded during planned demolition. During one of the tests, researchers collected radio propagation data before, during and after the implosion of a 14-story

³⁰ Kate A. Remley, et al, "Standards Development for Wireless Communications for Urban Search and Rescue Robots," Proceedings of the International Symposium on Advanced Radio Technologies, February 26-28, 2007. NTIA-SP-07-554 (Washington, DC: National Telecommunications and Information Administration, 2007), 66. http://www.its.bldrdoc.gov/pub/ntia-rpt/07-445/report_07-445.pdf (Accessed March 26, 2008).

³¹ National Institute of Occupational Safety and Health, *Current Status, Knowledge Gaps, and Research Needs Pertaining to Firefighter Radio Communication Systems* (Washington, DC: NIOSH, 2003), 37. <http://www.cdc.gov/niosh/fire/pdfs/FFRCS.pdf> (Accessed June 2, 2007).

apartment building near New Orleans, LA. The preliminary results of this experiment show that this type of building collapse can reduce the radio signal transmission significantly:

The preliminary results of this experiment show that this type of building can reduce the radio signal by as much as 50 dB by just entering the building. Once the building collapsed, attenuation can increase much more than this. This type of data helps us understand the communication problems with which first responders are confronted when they enter large structures, and the changes in propagation that occur when a building collapses.³²

More recently, spectral analysis testing was conducted in an apartment building, office hallway, oil refinery, and tunnel. The results of the testing will be discussed at greater length in Chapter III.

H. EFFORTS TO ADDRESS PROBLEMS

Innovative strategies have been attempted to extend the range of wireless robot operation. Space and Naval Warfare Systems (SPAWAR) – has worked on a novel concept that employs approximately five robots traveling together, forming a communications repeater chain link. It noted that many more could be accommodated by the network.³³ Just before the signal fades – essentially losing sight of the repeater robot – each repeater robot stops so that effective communications are maintained between lead robot and controller. More recently, SPAWAR has been testing a robot that deploys a small communications repeater brick at strategic locations in order to maintain the same link. While useful in some applications, the system relies on an 802.11b link according to papers that have been published, and may suffer some of the same problems witnessed

³² Christopher L. Holloway, et al, “Radio Propagation Measurements During a Building Collapse: Applications for First Responders” (*Proceedings of the International Symposium on Advanced Radio Technology, ISART 2005* Boulder, CO, March 2005), 61-63.
http://www.boulder.nist.gov/div818/81802/MetrologyForWirelessSys/pubs/R3_ISART05_Holloway_com.pdf (Accessed March 20, 2008).

³³ Narek Pezeshkian, Hoa G. Nguyen, and Aaron Burmeister, “Unmanned Ground Vehicle Non-Line-Of-Sight Operations Using Relaying Radios” (*Proceedings of the 12th IASTED International Conference Robotics & Applications*, Honolulu, Hawaii, 2006), 4.
http://www.spawar.navy.mil/robots/pubs/IASTED_ADCR.pdf (Accessed June 2, 2007).

in the US&R robot test events if other devices are operating in proximity. The specific issues affecting throughput drop in capacity with more than three or four links have also been explored, and would need to be considered for their influence on tactics.³⁴

Robot manufacturers have also recognized the problem and have started introducing more advanced communication technologies such as adaptive communications payloads.³⁵ While these efforts are a start to addressing the problem, they do not provide a comprehensive or interoperable solution for understanding the full nature of the problem.

I. GAPS IN CURRENT LITERATURE

The review of the associated literature shows that while researchers intuitively recognize that robots can provide utility to responders in a variety of response environments, few have specifically detailed methods of employment that take into account the limitations of wireless communications pertinent to specific environments. Very little has been written about potentially allocating additional spectrum or finding a solution that enables interference-free operation with existing spectrum. No work to date covers all aspects needed to address the issues detailing technology adoption of robots for accomplishing tactical objectives at emergencies and examining the influence of the wireless component in answering this problem.

J. SUMMARY

From this review, it appears that sufficient literature exists detailing the utility of robots for improving the safety of responder operations. The background development and current uses have been examined, along with possible future applications. Concurrently, the literature covering the wireless problems due to physical operating environment has been explored. Recently discovered problems due to interference have

³⁴Leland Joe, Isaac Porche III, *Future Army Bandwidth Needs and Capabilities* (Santa Monica, CA: Rand Arroyo Center, 2004), 4. http://www.rand.org/pubs/monographs/2004/RAND_MG156.pdf (Accessed June 2, 2007).

³⁵ George Bustilloz (iRobot Inc., Deputy Program Manager, Next Generation RCV), in phone interview with the author, November 24, 2006.

been referenced along with gaps in current knowledge. Thus, there exists room to contribute to the current knowledge base towards achieving reliable communications and control of robots in disaster situations. This will entail assessing the frequencies that would be most desirable due to their propagation characteristics, and then analyzing shortcomings of current operating protocols. Future recommendations will be made with regard to equipment and protocols needed to ensure the best opportunity for successfully employing robots for search operations.

III. METHODS AND DATA

A. TECHNOLOGY ACCEPTANCE MODEL FOR ROBOTS

Technology acceptance for computers was studied in the mid 1980s to help assess a worker's willingness to use computers in the workplace. In this section, the applicability of that model applied towards incorporating robots into fire department search operations will be assessed, and additional factors will be proposed for inclusion.

1. Technology Acceptance and Reliability

In order to achieve wider acceptance in the fire service for use in improving situational awareness, robots must be “deemed reliable” by the firefighters that seek to employ them. The fire service as a whole tends to eschew the adoption of new technology until it has demonstrated a certain level of reliability. While this may appear intuitive, it is useful to explore exactly what is deemed “reliable” means for determining how to best incorporate potentially life-saving devices into operational procedures. In the mid 1980s, researchers were interested in whether a new technology – personal computers – would ultimately be accepted. In his dissertation, which was published in 1989 in *Management Science* and *MIS Quarterly*, Fred Davis developed a Technology Acceptance Model (TAM) for assessing an end user's behavioral intent for using computers.³⁶ In this chapter, TAM will be used as a framework for considering the use of robots for gaining improved situational awareness in the fire service. A modified model will be offered, with specific examination of how wireless considerations influence this model.

In the paper “User Acceptance of Computer Technology,” Davis and others developed a model based on a widely accepted but generalized intention model – Theory of Reasoned Action (TRA) – that was “designed to explain virtually any human

³⁶ Fred D. Davis, Richard P. Bagozzi, and Paul R. Warshaw, “User Acceptance of Computer Technology: A Comparison of Two Theoretical Models,” *Management Science* 35, no. 8 (August 1989), 983.

behavior.”³⁷ Davis’s TAM more specifically postulated that behavioral intention (BI) for using computer systems is dependent upon the person’s attitude towards using the system (A) and the perceived usefulness of the system (U). Based on these factors, TAM posits that two particular beliefs – perceived usefulness and perceived ease of use – are of primary relevance for predicting behavioral acceptance. The model is depicted in the following diagram:

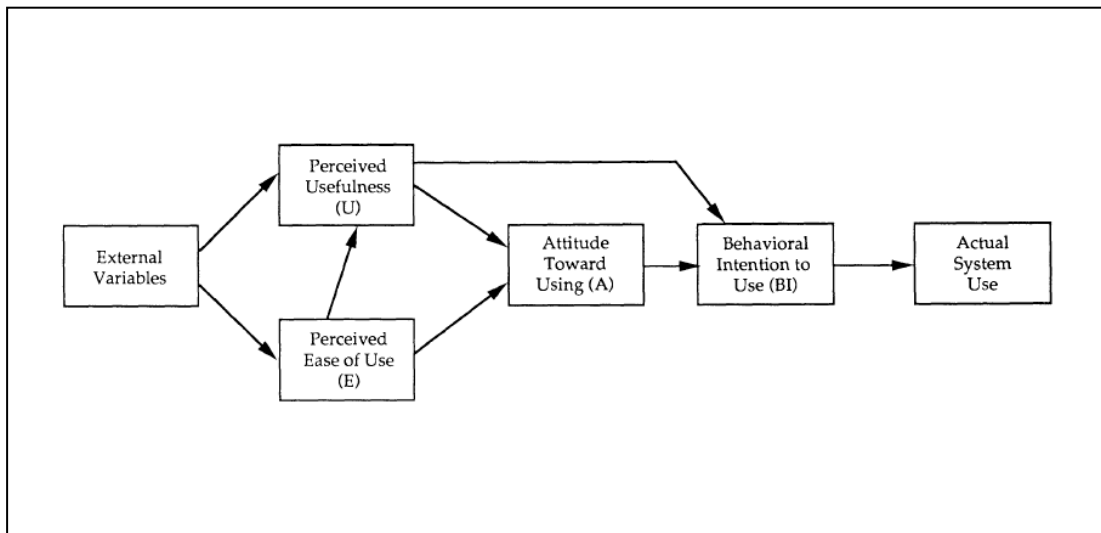


Figure 1. Davis Technology Acceptance Model (TAM): $BI = A + U$ ³⁸

Davis concludes from applying the model to an empirical study of graduate students utilizing computers for their coursework that:

- People’s computer use can be predicted reasonably well from their intentions.
- Perceived usefulness is a major determinant of people’s intentions to use computers.
- Perceived ease of use is a significant secondary determinant of peoples’ intentions to use computers.

³⁷ Fred D. Davis, Richard P. Bagozzi, and Paul R. Warshaw, “User Acceptance of Computer Technology: A Comparison of Two Theoretical Models,” *Management Science* 35, no. 8 (August 1989), 983.

³⁸ Ibid.

The author provides a caveat to his theory by warning that while ease of use is important, a system's usefulness is even more important, and that no amount of ease of use will compensate for a system that does not accomplish a useful task.

In 2005, Colvin and Goh presented a validation study of the technology acceptance model for police. They found the two-factor model hypothesized by Davis was not supported adequately. Instead, an exploratory factor analysis identified a four-factor model that indicated a good fit to the data. The four factors were labeled as ease of use, usefulness, information quality, and timeliness. Of these, the last two factors – information quality and timeliness – were the most important to patrol officers.³⁹

Both Davis' model of computer use by students and the Colvin and Goh application to patrol officers have limitations when applied to tactical emergency response situations. Graduate students choose to use computers on an individual basis in the Davis study, whereas implementing robot use in an operational setting involves integrating tactics with available technology. A recent study on robot introduction into a Swedish military team that specializes in urban intervention – Military Operations in Urban Terrain (MOUT) – attests to the complexity involved in deciding to adopt new technology for tactical deployment. During this nine month study – three months pre-study plus six months of training deployment – the authors tried to account for the ultimate willingness to adopt robots into operations and came to the following conclusions:

- Soldiers and lower level officers are generally skeptical about robotics until they get to fully know the system's abilities.
- Teamwork applications requiring individual robot interaction as well as organizational-level robot interaction will require significant efforts in development and training.
- A tolerant, supportive, and rewarding atmosphere will increase the rate of deployment.

³⁹ Caran Colvin and Angeline Goh, "Validation of the Technology Acceptance Model for Police," *Journal of Criminal Justice* 33, no. 1 (January/February 2005): 89.

- Basic skill development was important as an initial step before moving into more advanced deployment methods.
- Unsuccessful trials might have an overall negative impact that will prove difficult to overcome in gaining end-user confidence.
- Initial thoughts on robot application were unrealistic and did not correspond to final thoughts on best employment methods.

Specific tactical conclusions included an assessment that the main benefits of robots in MOUT were risk reduction and decreased weapon deployment. The major tactical drawbacks of employing robots were reduced pace and increased risk of detection. The soldiers also emphasized that a “tactical window of opportunity” exists during field operations that necessitates a robot be available for deployment within a few minutes. Fire service response for search and rescue is similar to MOUT in pace, and potentially more demanding in terms of terrain. The conclusions reached concerning MOUT robotic use provide insight when considering the introduction of robotics into tactical urban firefighting applications involving initial search of a potentially hazardous environment.

The authors of the Swedish MOUT study determined that robots fit into two general categories based on the intended function:

1. Performing tasks **in place** of soldiers – i.e., enabling EOD personnel to clear IEDs with robots instead of manually in bomb suits.
2. Performing tasks that might **augment** a soldier’s capability, but would require a significant modification to operating procedures – i.e., allowing the soldier to clear a minefield using a robot rather than altering his or her path or waiting for an EOD unit.

For fire service applications, categories 1 and 2 might be differentiated by the degree to which lives are perceived to be at risk. A category-1 situation may entail no perceived life risk (except that of the responder) and a less critical time constraint for investigating a situation. Category 2 might be considered as having a higher potential life-risk situation, and would necessitate a more rapid intervention – be it responder or robot.

Robots could most easily be introduced into fire department applications in the first case because time is available to gain situational awareness. If an area is unstable, but firefighters know with a reasonable degree of certainty that no lives are at risk, then greater time exists to wait for the delivery of a robot to the scene of an incident, to employ the robot into the immediate area, and to tolerate setbacks while achieving the search mission. A specialized technical rescue unit would also know into which situations to substitute a robot, such as in acquiring video of a crack or deformation in an area of an unstable building, provided all civilians had self-evacuated. While preparations are being made by responders to support the building, a robot might be introduced to gain information that may obviate the need to shore up the building in order for an engineer to evaluate it.

However, as the exigency of the situation increases – i.e., the increased perception that civilian lives may be at risk (category 2) – the need for well-defined employment guidelines and reliable systems becomes concurrently greater. Responders will assume greater personal risk to conduct searches because civilian lives are perceived to be at stake. In SPAWAR’s after-action report from the WTC response, the authors note that “team leaders were impressed that the first-responders were willing to risk their own lives as a matter of course and only consider the robot applications when time permitted.”⁴⁰ In order for firefighters to employ robots in tasks that they normally accomplish themselves when lives are perceived to be at risk, each component – time for delivery, time for employment, and time to accomplish the mission – becomes correspondingly more critical and needs to be considered in developing realistic response plans involving robots. These considerations might assist an agency to determine if it would centrally locate multiple robots or instead provide a few strategically located units with a single robot. Setup and delivery time to the point of insertion also are key logistical factors to be considered. Finally, the time necessary for an operator to conduct a search using a robot for gaining the necessary video, sensor or other information also needs to be considered.

⁴⁰ After Action Report to the Unmanned Ground Vehicles/Systems-Joint Program Office: Center for the Robotic Assisted Search and Rescue (**CRASAR**), section 4.2, 13.

All of these considerations must be weighed against the opportunities that the use of a robot may afford in gaining information during the initial phases of an incident involving a search for life. In some instances, responders have no choice but to wait for specialized equipment in order to shore an unstable structure before entering it. At a hazardous materials release, firefighters may need to wait for specialized units to arrive in order to bring the appropriate chemical protective suits for entering a contaminated area. In the event of a reported explosion, responders may need specialized breathing equipment to be delivered to the scene of an incident prior to advancing into a very long smoke-filled tunnel. The window of opportunity for employing a robot exists during the time period when the appropriate measures are being taken parallel to the normal response plans. In the instance where a robot successfully enters an area and delivers video that confirms no victims are present, then a team of firefighters has saved considerable time in not having to shore an area or don protective equipment. The Incident Commander must determine whether the time and opportunity cost in terms of committing manpower to the task of deploying a robot is worth the information that might be gained and/or increased safety margin that would be realized. Most importantly, plans need to be developed prior to an incident in order to afford an IC a realistic capability.

The Swedish MOUT study draws a conclusion that “gaining insight into the full potential of new technology by including the second category would require a substantial redesign of doctrines, including identification of niches that might not have been targeted before.”⁴¹ New applications may also be found by placing man-portable robotic devices into non-traditional employment scenarios. In order to accomplish this, robots would need to be integrated more thoroughly into existing response plans, with tactics developed to match the operating environment.

2. Application of Tactical Employment Categories to TAM

Through utilizing robots at training events and actual incidents, a responder operating a robot would receive positive or negative reinforcement that may affect his or

⁴¹ Lundberg, “Long-Term Study of a Portable Field Robot in Urban Terrain,” 646.

her attitude toward employing robots in similar situations in the future. By developing specific tactics for both category 1 and category 2 situations for employing these devices a response agency may perceive a system as more useful, since the Incident Commander and operator will have better guidelines that afford a more clearly defined concept of when to employ a robot, which may translate into a behavioral intent to employ it more often. Well-defined tactics need to take into account the time required for delivering the device to the scene, transporting it to the point of insertion, exploring the area, and relaying information back to the operator and possibly command post. The types of information of interest include video, thermal imaging, radiation detection, chemical sensing, etc. Determining the device's limitations becomes a key part of establishing the bounds of usefulness. The physical mobility factor will be explored briefly followed by a more in-depth look at the wireless control link.

3. Reliability of the System

In addition to looking at well-defined methods, the ultimate adoption of a new technology will depend on its perceived usefulness, and will be influenced by the performance of the system based on the operating environment. Reliability of the system is predicated upon whether the system performs as anticipated. For instance, upon activating the robot, it should be able to perform a system check and navigate flat terrain within a short distance (20 feet) from the operator without failure. However, it is still another issue to send the robot 20 feet onto a steep, rocky rubble pile and expect it to perform equally well.

Although less intuitive, the wireless aspect of employing robots similarly needs to be considered in context with the surrounding environment. For example, in comparing the performance of robot operation in a small tunnel verses a big tunnel, one should not expect the same operating range. Similarly, a narrow street will display different performance characteristics compared to a wide street in a downtown area. In this instance, the external factors of the physical environment affect the operating range that should be expected. Through experience, an operator may gain a feel for how a robot will perform in some familiar settings. However, without considering the external factors

of frequency, bandwidth, and antenna heights more closely, a system may be perceived as reliable in one setting, yet unreliable in a slightly different environment. The issue may not be the reliability of the system per se, but instead an unrealistic expectation of the operator.

Based on the additional factors of well-defined tactics and reliability, a technology acceptance model for incorporating robots into the fire service might be viewed in Figure 2 as follows:

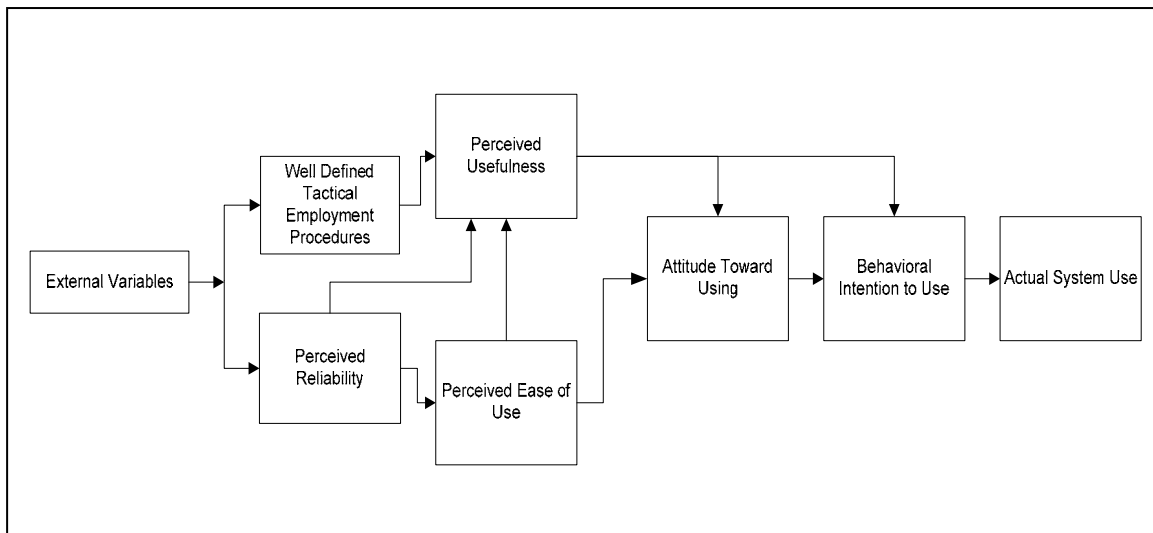


Figure 2. Modified Technology Acceptance Model⁴²

4. External Factors

In the case of a man-portable robot, factors such as mobility, operating life, and wireless control are among the contributors to perceived reliability of the system, as well as influences on the development of well-defined tactical employment procedures. The mobility component might include factors such as the consistency of the terrain (dirt, sand, snow, or concrete) and the robot's mechanical ability to handle such systems. Intrinsic to reliability of the system is whether it operates without "throwing a track" and breaking down in situations it is anticipated to handle. A more challenging factor that

⁴² Fred D. Davis, Richard P. Bagozzi, and Paul R. Warshaw, "User Acceptance of Computer Technology: A Comparison of Two Theoretical Models," *Management Science* 35, no. 8 (August 1989), 985.

influences the reliability of the system involves maintaining the wireless link between control unit and robot, depending on the external factor of the operating environment. During the employment of robots at the 9-11-01 WTC response, responders found significant problems with operating robots in confined areas, and lost reception at distances as short as 30 feet. Casper and Murphy detail the communication problems experienced in more depth:

Communication dropouts may have impacts on user acceptance. The communication dropout altered the rescuers' confidence. The Solem was lost during the seventh deployment due to communication dropout. Twenty-one complete communication dropouts (equating to 1:40 minutes) occurred during the seventh deployment drop which lasted 6:55 minutes... The dropout incident affected the confidence rescuers had in the robots. The rescuers questioned how to get the robot back, if the robot would be operable, what the operators were going to do, and whether they should put someone in the unsafe void to retrieve the robot. ⁴³

At a NIST-managed training event, USAR responders found that interference with other robots operating at the same time was more problematic than operating range. In some cases one operator inadvertently took control of a neighboring robot and ran it into a wall. In the Swedish MOUT study, soldiers also indicated that the main technical drawbacks were the narrow field of view, poor image quality, and limited radio range. The authors concluded that the "capacity and range of the radio link greatly affects the usefulness of the robot system."⁴⁴ In each of these cases the perceived reliability of the wireless link is critical to the usefulness of the device.

In looking specifically at the wireless communications link of the modified TAM, the external variables that influence perceived reliability, which in turn impacts usefulness, include:

- Physical Environment (tunnels, downtown urban cities, etc.). Large structures consisting of dense building materials such as steel-reinforced concrete, bullet- or sun-resistant glass, etc., significantly degrade the

⁴³ Casper, "Human-Robot Interactions during the Robot-Assisted Urban Search and Rescue Response at the World Trade Center," 367.

⁴⁴ Lundberg, "Long-Term Study of a Portable Field Robot in Urban Terrain," 644.

transmission through structures. The physical shape of the space also imparts a frequency selective attenuation component – that is, signals at some frequencies propagate farther than at others in basements, tunnels, and hallways because the geometry of the structure affects signal travel.

- Operational Environment - The function that the agency (fire department in this case) performs with respect to operating at an emergency. Firefighters are tasked with gathering information at a hazardous materials incident, and searching an area to ensure that people have been evacuated. New equipment must fit within the operational framework of the organization employing it.
- Radio Environment - The transmitter and receiver hardware/software/protocols that go into controlling a robot and transmitting video. Further, it is important to maintain the control link beyond the point when the video link “drops out” so that the robot can be recovered by retracing its path to the point where it regains its video.

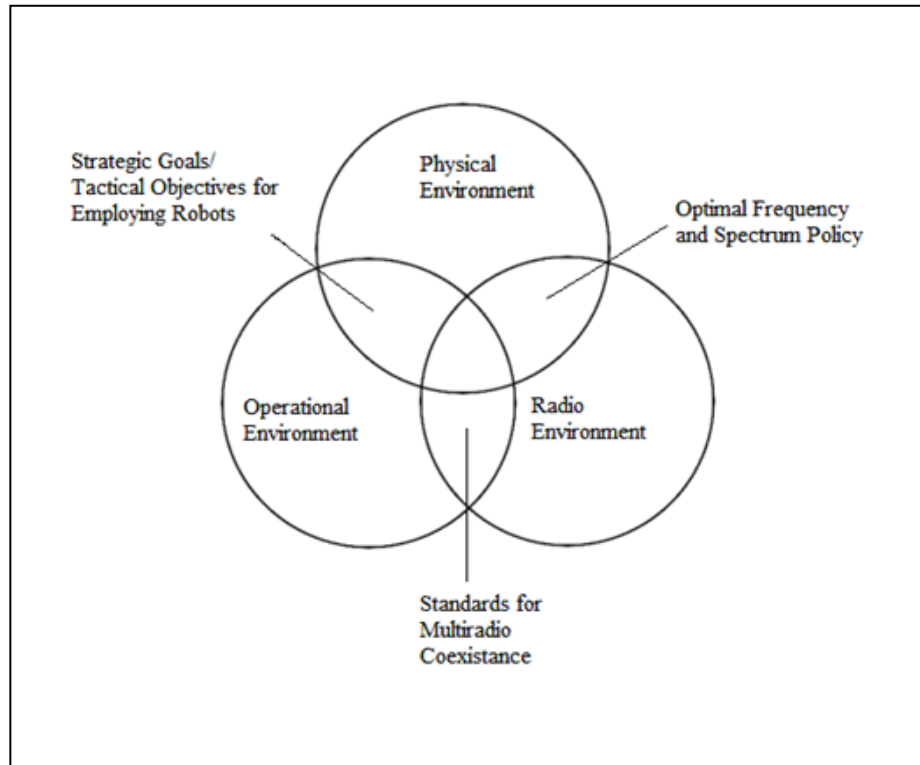


Figure 3. External Wireless Variables for TAM

Figure 3 shows the three main environments, with specific functional overlap, which might be considered as the following:

- Strategic Goals/Tactical Objectives - the intersection of the Physical and Operational Environments where the goals and tactics for employing a robot are developed. For instance, in one scenario it will generate a requirement to maintain a safe operating distance. The range of the robot will need to be taken into account to determine whether it might be successfully employed in this instance.
- Optimal Frequency Selection - the intersection of the Physical Environment and the Radio Environment. Based on specific physical settings – tunnels, dense buildings, etc., – some frequencies enable a longer range of operation. Capacity also varies as the received signal-to-noise (S/N) ratio, and is influenced by the physical environment of operation.
- Standards for Multi-radio Coexistence – the intersection between the radio and operational environments. Many users operating in the same bands that robots might possibly utilize may result in interference that causes signal degradation or complete dropout. Consideration should be given to the need for standards to govern coordinated use by multiple responders. The operations dictate who will be transmitting, and how many robots or other wireless devices will be utilized in the same area.
- Quality of Service (QoS) and Operating Range - the center of the diagram. Near real-time video dictates that minimal latency (average time for bits to arrive) and jitter (variation in time for bits to arrive) occur during signal transmission so that the operator has a signal that is useable for controlling the robot. A certain QoS is required given an anticipated range of operation.

Based on the aforementioned factors listed in Figure 3 above, each of the environments will be explored in more depth, setting the stage for three scenarios to illustrate the interplay of these factors.

B. OPERATIONAL ENVIRONMENT – OPPORTUNITIES FOR EMPLOYMENT

When an emergency is reported, the exact nature of an incident is almost never immediately known. The 1993 World Trade Center bombing was initially dispatched as a transformer explosion, but in fact turned out to be a truck bomb that exploded and blew a hole from the B2 parking garage area through four levels of reinforced concrete.⁴⁵ Upon arrival on scene, response units today must consider the very likely event of an explosion and/or release of chemical, radiological, or biological agents.

Strategically, the potential presence of toxic materials adds a considerable burden on responders by requiring them to take protective actions. Firefighters may need to don encapsulating suits that limit their operational time, and additional manpower must be committed to decontamination efforts upon leaving the contaminated area. This in turn reduces the balance of resources available to execute the remainder of the mission. Accompanied with any explosion, responders must also consider the potential that there may be a secondary device set to injure and disrupt rescuer operations. The following are a sampling of situations where robots may fill a tactical niche that may lead to a strategic benefit in response operations.

1. Transportation Emergencies – Terrorism and Accidents

Each day millions of people in the United States commute to work via automobile, bus and subway. In New York City alone, 4.7 million passengers travel its subway system - consisting of 26 routes that cover 660 miles of track, making it the world's fourth busiest subway system.⁴⁶ Unfortunately, these systems also present attractive targets for terrorists due to the concentration of people that travel these spaces, and the open nature of the rail system that allows for unimpeded transit. While no

⁴⁵ U.S. Fire Administration, "The World Trade Center Bombing: Report and Analysis," New York City, NY, USFA-RR-076, (Washington, DC: Department of Homeland Security, February 1993) 2. <http://www.usfa.dhs.gov/downloads/pdf/publications/tr-076.pdf> (Accessed March 10, 2008).

⁴⁶ "Oversight: MTA and NYC Subway System Emergency Evacuation Plans, Protocols, and Procedures," Briefing Paper of the Governmental Affairs Division, Transportation Council, New York City, January 30, 2007. <http://webdocs.nyccouncil.info/attachments/76003.htm> (Accessed March 4, 2008).

successful attacks on rail systems have taken place recently in the United States, the FBI and local police departments have thwarted several planned attacks against the New York subway system including a plot to bomb the subway complex at Atlantic Avenue, Brooklyn on July 31, 1997,⁴⁷ and more recently the arrest of two Islamic radicals for plotting to bomb the Herald Square subway station a week before the Republican National Convention in August of 2004.⁴⁸ Public transit systems have been subject to successful attacks internationally, and a listing of the more notable ones includes:

- March 20, 1995 - Sarin nerve gas was released in the Tokyo subway system, killing 12 people and injuring more than 5,500.⁴⁹
- February 6, 2004 - An explosion, caused by suicide bombers, ripped apart a train car in the Moscow metro killing 39 people and wounding at least 129 others.⁵⁰
- July 7, 2005 - The London Underground was hit with three explosions that were detonated by suicide bombers. The explosions killed 52 people and injured over 700.⁵¹
- February 2007 – Explosives in two suitcases on a Delhi train bound for Lahore killed at least 66 people and injured 13 others.⁵²

While intentional attacks are certainly high among potential threats to people that ride mass transit, danger also exists from unintentional emergencies that cause service disruptions. In sum, local responders must prepare for the following:

⁴⁷ “Oversight: MTA and NYC Subway System Emergency Evacuation Plans, Protocols, and Procedures,” Briefing Paper of the Governmental Affairs Division, Transportation Council, New York City, January 30, 2007. <http://webdocs.nyccouncil.info/attachments/76003.htm> (Accessed March 4, 2008).

⁴⁸ Ibid.

⁴⁹ Nicholas D. Kristof, “Mysterious Fumes in Japan Store Send 24 to Hospitals,” *New York Times*, April 21, 1995.

⁵⁰ Jill Dougherty, “Moscow Metro Blast Kills 39,” *Cnn.com*, February 6, 2004. <http://www.cnn.com/2004/WORLD/europe/02/06/moscow.blast/> (Accessed 3/4/2008).

⁵¹ “Bombers Target London,” <http://www.cnn.com/SPECIALS/2005/london.bombing/> (Accessed March 4, 2008).

⁵² “Leaders Condemn India Train Blast,” *BBC News*, February 19, 2007. http://news.bbc.co.uk/2/hi/south_asia/6375749.stm (Accessed March 4, 2008).

- Fire/Smoke condition in tunnels
- Mass customer evacuation from trains
- Total/partial power failure
- Collisions/derailments – passenger service trains
- Bomb threats and/or actual explosive devices
- Nuclear/biological/chemical release
- Flammable/combustible liquids/vapors

Among the most challenging considerations for transportation emergencies is the potential for an incident to take place in a deep under-river tunnel that may span thousands of feet. Since 9/11/01, the NYC Metropolitan Transportation Authority (MTA) has consistently listed their 14 under-river subway tunnels among the most vulnerable of its critical infrastructure.⁵³

Tunnel emergencies magnify response considerations, including the duration of the incident and the increased effects from heat and smoke. In order to travel the long distances safely, special breathing apparatus such as is used for mine rescue may be needed, and some cities have acquired this equipment after recognizing the hazard. In addition, the structural integrity of the tunnel may also be compromised. Secondary hazards may result from the effect of an explosion or fire on the tunnel infrastructure. In the 1996 English Channel Tunnel fire, significant portions of the overhead concrete underwent explosive spalling due to exposure to heat, endangering responding firefighters. More recently, the Port Authority of New York and New Jersey conducted a vulnerability analysis of their underwater tunnels linking the two states and found them to be vulnerable to attack.⁵⁴

⁵³ Sewell Chan, “Who’s Watching the Underwater Tunnels?” *The New York Times*, July 20, 2005. <http://www.nytimes.com/2005/07/20/nyregion/20tunnels.html?n=Top/Reference/Times%20Topics/People/F/Fahim,%20Kareem>, (Accessed March 4, 2008).

⁵⁴ William K. Rashbaum and William Neuman, “PATH Tunnels Seen as Fragile in Bomb Attack.” *The New York Times*, December 22, 2006. http://www.nytimes.com/2006/12/22/nyregion/22security.html?_r=1&th&emc=th&oref=slogin (Accessed March 4, 2008).

Based on the aforementioned considerations, tactical opportunities exist to work robots into standard operating procedures. Since a significant potential exists for numerous civilian lives to be at risk in the event of an attack, plans need to be devised beforehand that take into account goals, tactics and capabilities for each unique environment. The document “Robotic Devices: A Guide for the Transit Environment” by the Transit Cooperative Research Program (TCRP) for the Transportation Research Board (TRB) of the National Academies provides a basis for considering specific deployment challenges by identifying the expected operating environment and developing requirement specifications (although not directed specifically toward tunnel emergencies).

In another report by the TRB – “Making Tunnels Safe and Secure” – additional detail regarding the operating environment is provided. A comprehensive operational plan for employing robots needs to incorporate information from these reports, while also taking into account logistical concerns for delivering a robot to a scene. In most situations involving passenger trains, lives are potentially at risk and responders must conduct searches in a timely manner, and the time constraints for delivering a robot are concurrently more stringent. This may necessitate purchasing additional man-portable devices, training more members, and making the necessary provisions for delivery to the scene of an incident. There are certainly trade-offs in terms of operating cost, time commitment, and training. However, the additional requirements need to be balanced by the potential increase in operator safety – a subject that will be difficult to quantify or even qualitatively assess until robots begin to be employed in such circumstances.

Additional considerations in planning for a response include recognizing that people may be directed to evacuate from a particular end of the tunnel (either subway or automobile) with smoke-ejecting fans being activated in an attempt to draw smoke in the opposite direction from the evacuation. An opportunity may exist to employ a robot to search from the end that is opposite to the one in which people are directed to evacuate, particularly if it is the long end to reach the train. In the case of an automobile tunnel, car traffic would most likely be stopped at the point of the fire. Visual navigation via the robot’s standard video camera may be poor or impossible due to the smoke being

generated and pulled in that direction. This may necessitate navigation via a thermal imaging camera attachment. In the future an advanced form of flash Laser Imaging Detection and Ranging (LIDAR) may provide visual navigation through light smoke conditions. The goal for such an operation would be to search the track-bed/roadway for people that may have attempted to exit the train or vehicles, and have become incapacitated by the smoke and toxic gasses issuing from the train or automobile.

Goals for employing robots in difficult-to-access transportation emergencies might include acquiring images of the damaged area of the tunnel and or vehicle. In some situations, after the robot is deployed it might simply provide video of responder operations as the incident unfolds. It might also serve as a communications link for responder telemetry data, along with devices such as wireless portable thermal imaging and video cameras. The goal may be to advance in front of the responders 300 meters at a time to provide chemical and radiological readings, and then to return video and data the length of the tunnel upon arrival. Operational considerations would need to be developed in conjunction with the physical and radio environments, as will be discussed later in Chapter IV.

In order to traverse long subway tunnels, a robot's chassis and treads must be selected to clear track-bed impediments. In the future, specific adaptations might be constructed to allow the robot to ride one of the track rails, or to sit atop a platform that is made to sit upon a single rail. Potentially, a hybrid system involving two pieces might be useful. The bottom platform might even deploy a tether for hard-wired control, and the robot would ride upon the delivery platform to the location of the disruption, and then dismount at the point where damage precludes the platform from continuing. From that point the robot would be wirelessly controlled through the tethered platform to investigate an incident. Additional study would be needed to consider the merits of such a system as it introduces complexity, and with complexity there is more opportunity for something to go wrong.

Recently, the Transportation Security Administration (TSA) has begun to investigate suitable robot platforms for use in under-river subway tunnels to gain

situational awareness in the event of an incident.⁵⁵ In Europe, an association called RUNES is developing plans that include a futuristic scenario that includes employing robots for responding to tunnel emergencies. Past fires, such as the 1999 fire in the Mont Blanc Tunnel connecting France and Italy that killed 39 people, and the 2001 fire in Switzerland's Gotthard Tunnel that claimed 11 lives, provided much of the impetus behind this effort.⁵⁶

2. Chemical, Biological, Radiological, Nuclear, Explosive (CBRNE), and Hazardous Materials Emergencies

Emergency responders are instructed to be aware that calls that are dispatched reporting multiple medical emergencies may in fact turn out to be employment of a chemical agent involving nerve, blister, choking, or blood agents. Another concern for responders includes a radiological dispersion device (RDD) that is intended to disperse radioactive material when coupled with an explosive device, thereby spreading minute particles of radioactive material to contaminate the surrounding area. Both types of scenarios are included among the National Planning Scenarios. In either case, a robot might be employed for initial reconnaissance, initial perimeter monitoring, or extended periodic monitoring. Among the key considerations for effective robot employment is utilizing sensor packages that can be integrated into the standard communications package in such a way that information can be wirelessly relayed to the operator in real-time. Sensors will also need to reset quickly in the event of saturation – a problem that is equally significant for handheld units that responders currently use for hazmat situations.

Each year thousands of highway and rail shipments bring hazardous materials in close proximity to urban environments. Derailments and spills occur on a frequent basis, sometimes with deadly consequences. Due to the risk and potential consequences of a release, a chlorine tank explosion is listed as one of the National Planning Scenarios,

⁵⁵ “Robots in Tunnels: A New Environment for Technology that Works,” (Transportation Security Administration) http://www.tsa.gov/press/happenings/robots_in_tunnel.shtm (Accessed March 4, 2008).

⁵⁶ Ed Comeau and Bill Flynn, “The Big: NFPA 502 Drives Safety of the World’s Biggest Tunnel System,” *NFPA Online Journal*, (May/June 2003) <http://www.nfpa.org/archivedJournalHome.asp?categoryID=690&src=NFPAJournal>, (Accessed March 4, 2008).

along with the release of toxic industrial chemicals (TIC). In 2005 a train derailment in Granville, SC resulted in the release of chlorine from two railcars, leading to nine accompanying deaths. Many hazardous chemicals are shipped through urban areas in bulk each day, and robots hold the potential for assisting hazardous materials teams in gaining situational awareness in a safer manner.

3. Emergencies - Technical Rescue (Confined Space, Collapse) and Utilities

Firefighters are additionally tasked with responses involving unstable structures and utility emergencies. As a city's aging infrastructure deteriorates, firefighters are increasingly called upon to assist engineers with determining the immediate stability of a structure and taking the appropriate steps to ensure the engineer's safety when inspecting an area of concern. An opportunity may exist for further investigating a situation without exposing humans to the risks associated with inspecting the building or facility. This may also obviate the need to shore an area if the intent is to search an area simply ensure that no person is trapped.

At times workers enter confined spaces with inadequate respiratory protection, and succumb to inhaling noxious gases. Among the key considerations that a responder must decide upon is whether the effort is a rescue or recovery. A situation such as this one might entail simply lowering a small robotic device to obtain video and atmospheric data while a rescue effort is being mounted. While the information may not be sufficient for making a determination, it might provide information about the layout of the area. In the near future, automated mapping applications may enable the creation of detailed maps prior to entry.

4. Strategic Goals and Tactical Objectives

Among the strategic priorities that are considered during any fire department response are life safety (both civilians and operating forces), incident stabilization, and

property and environment conservation.⁵⁷ The Incident Commander (IC) sets overall strategic goals guided by these criteria. Essentially, a strategic goal is a game plan for managing the incident safely. After establishing command, an IC must conduct some form of hazard assessment. The extent of this will vary depending upon the incident and the potential risk involved. In a hazardous materials release, for instance, prior to committing members, the IC must assess the nature of the hazard, extent of release of the material, and potential for further release or harm. In situations involving technical rescue or collapse, a similar assessment is made regarding whether the situation is a rescue or recovery, and whether the area is structurally sound and people should be committed to searching it. It is during this phase that an IC will determine whether there will be an offensive, defensive, or non-intervention approach to the situation based on the strategic priorities, time factor, and resources available. Once a strategy is selected, then Branch and Sector leaders will establish tactical objectives in order to accomplish the goal.⁵⁸

In considering whether to utilize a robot at an incident, a department must have a plan in place that takes into account:

- Strategic Goal – Category 1 or 2 employment scenario depending on exigency of the situation – i.e., potential life risk or time constraints generated by an incident that has not been adequately stabilized.
- Tactical Objectives – i.e., obtaining video, high resolution still image, thermal image, LIDAR/LADAR image, chemical/radiation detection, mapping, etc.
- Capabilities – likelihood of the robot meeting the situational challenge, i.e., operating within wireless range, physically traversing the terrain, retaining sufficient power supply, etc.
- Timeframe

⁵⁷ Steve Fruchtmann and others, *IAFF Training for Hazardous Materials: Technician Instructor Guide Module 10: Incident Management* (Washington, DC: International Association of Firefighters, 2002), 10-11.

⁵⁸ Gregory G. Noll, Michael S. Hildebrand, and James G. Yvorra, *Hazardous Materials: Managing the Incident 2nd Ed.* (Stillwater, OK: Fire Protection Publications, 1995), 353-359.

- Delivering robot to an incident
- Inserting robot into scene and obtaining information
- Opportunity cost for committing assets/manpower to this function.
- Quality of Information – Will the information received meet the IC’s information need? – i.e., are the sensors carried by the robot adequate for obtaining useful video, or detecting the hazard and quantifying it to a sufficient level?

5. Additional Considerations

In developing robots to be applied to the situations described, consideration should be given to ensuring that robots are designed to the same safety levels as other firefighting and hazardous materials response equipment. Devices used in situations involving materials that may generate flammable environments typically are either intrinsically safe or nonincendive. Among the conclusions reached by the NASA Jet Propulsion Laboratory study on hazmat incident robots, the authors note the need for a device that either does not generate sparks and/or is constructed in a manner that does not allow the sparks to propagate to the outside. Robots should also be able to be decontaminated with minimal effort, and be equipped with consumable items such as tracks designed to be easily replaced in the field.⁵⁹ Additional issues of size, mobility, power, operator interface, and communication should be considered for the specific task of gaining situational awareness during an initial deployment at a hazardous materials incident.⁶⁰

The sensor information provided in some situations may be the most vital information that a robot might return, and would need to meet the operational challenges of normal hazardous materials response in addition to a weapon of mass destruction (WMD) event. The US&R robot requirements document included a provision for a graduated set of sensor capabilities that would be advantageous to add to a robot sensor

⁵⁹ Decontamination is an area of current discussion in the ASTM E 54.08.01 Standards for Robots for USAR.

⁶⁰ Welch, *Requirements for Robots Utilized at HAZMAT Incident Sites*, 2.

package. In increasing order of complexity, it included providing atmospheric monitoring for oxygen, combustible gases, toxic gases (carbon monoxide), WMD detection/identification, toxic industrial chemical (TIC) detection/identification, and categorization and/or identification of unknowns.⁶¹ With the advance of technology, detection equipment continually reduces in size. A tradeoff now exists between the cost savings for mounting existing equipment onto a robot and the advantages of packaging more sensors into the equivalent space on the robot. Since standards are being developed within ASTM for handheld WMD detection and also for robotics in US&R applications, an important factor going forward will be developing plug-and-play capability amongst different manufacturer's devices so that sensors can be used on multiple platforms. The data that the sensor provides also needs to be relayed via the main wireless control link. A common hard-wired interface standard needs to be developed to transfer the information between the sensor package and the main communications device. If a wireless personal area network, similar to Bluetooth, is used to relay data to the main communications module, it must be robust enough to work reliably in extremely adverse radio frequency (RF) environments.

C. PHYSICAL ENVIRONMENT

Each of the aforementioned operational concerns exists in a physical setting. Tunnels vary in size and shape. Industrial facilities contain substantial amounts of steel piping and machinery. High-rise buildings line streets, creating a canyon-like effect; hence the name "urban canyon." Each physical setting affects signal propagation in a slightly different way. In this section, relevant simulations will be presented to illustrate concepts based on mathematical formulas found in the literature. The simulations were developed using MATLAB programming language and are used to illustrate propagation effects for a range of frequencies of particular interest to public safety agencies.

Theoretical models are developed to account for anticipated losses. Some methods are based on statistical averaging for a large area such as a neighborhood, while

⁶¹ Messina, Statement of Requirements for Urban Search and Rescue Robot Performance Standards-Preliminary Report, Appendix C - Hazmat Sensing Requirements, 67.

others are developed for the specific sites being considered. Even the best models are only approximations, because factors such as absorption, reflection, diffraction, and scattering impact the theoretical results. The frequency, which is inversely related to the wavelength of a radio wave, plays an important role in determining how far a signal will travel. In many environments, a higher-frequency wavelength will be much smaller than the objects it contacts, allowing the signal to be modeled as a collection of rays that are partially reflected, partially transmitted, and partially absorbed.⁶² In this chapter, these factors will be considered in greater detail, along with an assortment of models that can be useful for assessing the loss (or gain) between the control unit and robot. The purpose is to present some basic background understanding of propagation, along with a few relevant models in order to explore the link between the frequency of the transmitted wave and the environment.

Figure 4 shows the electromagnetic spectrum classification of bands, along with the wavelength that corresponds to each frequency. For example, the UHF band of interest for much of first responder communications covers the frequencies from 300 MHz to 3000 MHz (or 3 GHz), with corresponding wavelengths ranging from 1 meter down to 10 centimeters.

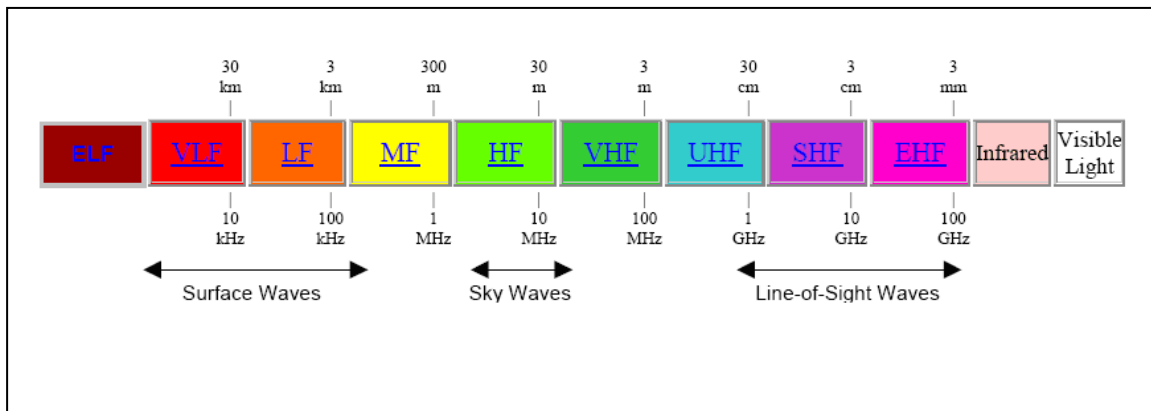


Figure 4. Radio Spectrum⁶³

⁶²Vinay Sridhara and Stephan Bohacek, "Realistic Propagation Simulation of Urban Mesh Networks," *Computer Networks* 51, no. 12 (August 2007): 3396. <http://dx.doi.org/10.1016/j.comnet.2007.01.035> (Accessed March 4, 2008).

⁶³Figure 4 from National Institute of Occupational Safety and Health, *Current Status, Knowledge Gaps, and Research Needs Pertaining to Firefighter Radio Communication Systems* (Washington, DC: NIOSH, 2003), 37. <http://www.cdc.gov/niosh/fire/pdfs/FFRCS.pdf> (Accessed March 2, 2007). And Adapted from Allocation of Radio Spectrum in the United States, http://www.jneuhaus.com/fccindex/spectrum.html#table_of_contents (Accessed March 4, 2008).

1. Free Space Path Gain (Loss)

Free space transmission involves a radio wave that is transmitted without encountering an obstruction. A more exact definition is as follows: “A free-space transmission path is a straight-line path in a vacuum or in an ideal atmosphere, and sufficiently removed from all objects that might absorb or reflect radio energy.”⁶⁴ In practice free space propagation conditions are approximately achieved when the Fresnel zone about the transmitting and receiving antennas is free of any objects. Figure 5 illustrates the Fresnel zone between a transmitter and receiver, which is an ellipsoid of revolution such that the distance from the transmitting antenna to the ellipsoid and then to the receiving antenna is bigger than the straight line distance between antennas by one-half wavelength.

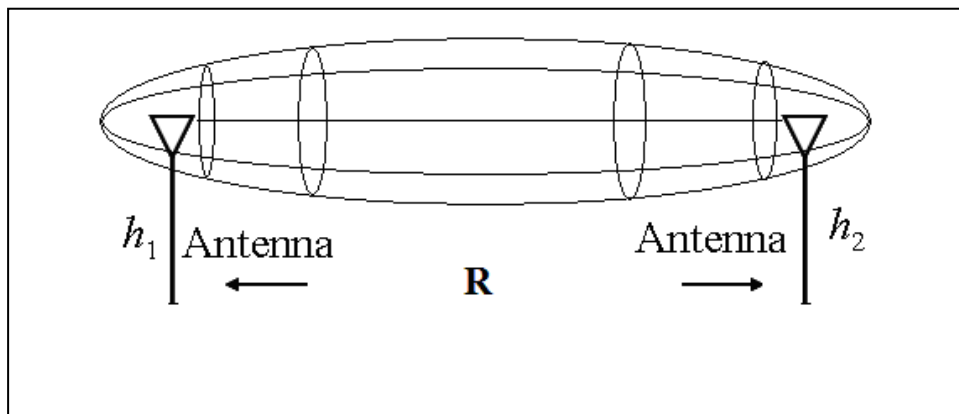


Figure 5. Fresnel Zone about the Transmitting and Receiving Antennas

The path gain is defined as the ratio of received power to transmitted power. For typical radio propagation, this ratio is always less than unity, and is typically many orders of magnitude smaller. Path loss is the reciprocal of path gain, and is usually expressed in decibels (dB). Figure 6 shows the free space path gain between small antennas expressed in dB as a function of antenna separation for different frequencies. (When expressed in dB, path gain is negative and path loss has the same magnitude, but is expressed as a positive value.) Note that at 600m, the path gain for a 400 MHz signal is -80 dB. Thus

⁶⁴ K. Bullington, “Radio Propagation at Frequencies Above 30 Megacycles,” *Proceedings of the IRE* 35, no. 10 (October 1947), 1122.

for 1 watt of transmitted power, the received power will be 1×10^{-8} watts. The free space path gain is characterized by $1/R^2$ distance dependence, where R is the distance between antennas.

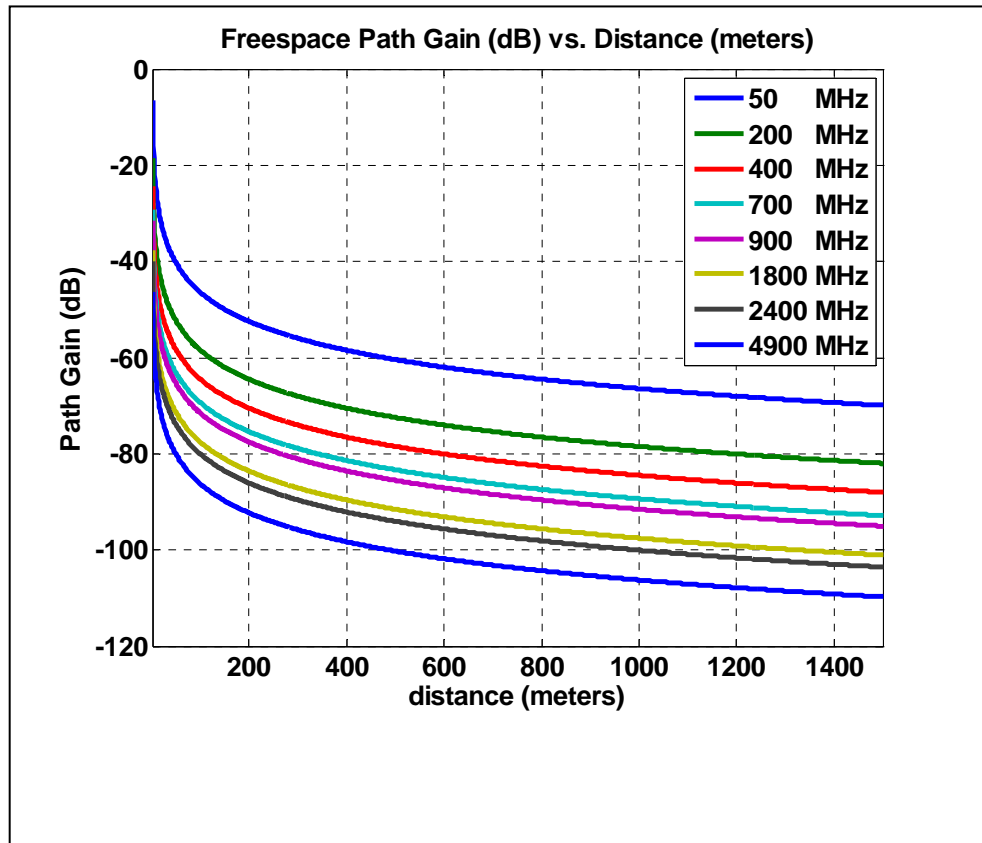


Figure 6. Freespace Path Gain vs. Distance for 50MHz to 4900MHz

2. When Radio Waves Collide: Transmission, Reflection, Scattering, Fading

Without any obstructions, radio propagation follows the free space curve as shown above. However, radio waves normally encounter obstacles that change the characteristics of the received signal. Many environments will cause reflections and scattering of rays (radio waves), causing a form of self-interference. When waves arrive out of phase, they may cancel each other out (multi-path fading). However, some reflections will combine to raise the received signal strength from the free space value.

For single-frequency signals, the result is a standing wave pattern in space of alternating regions where the signal is weak and regions where it is strong.

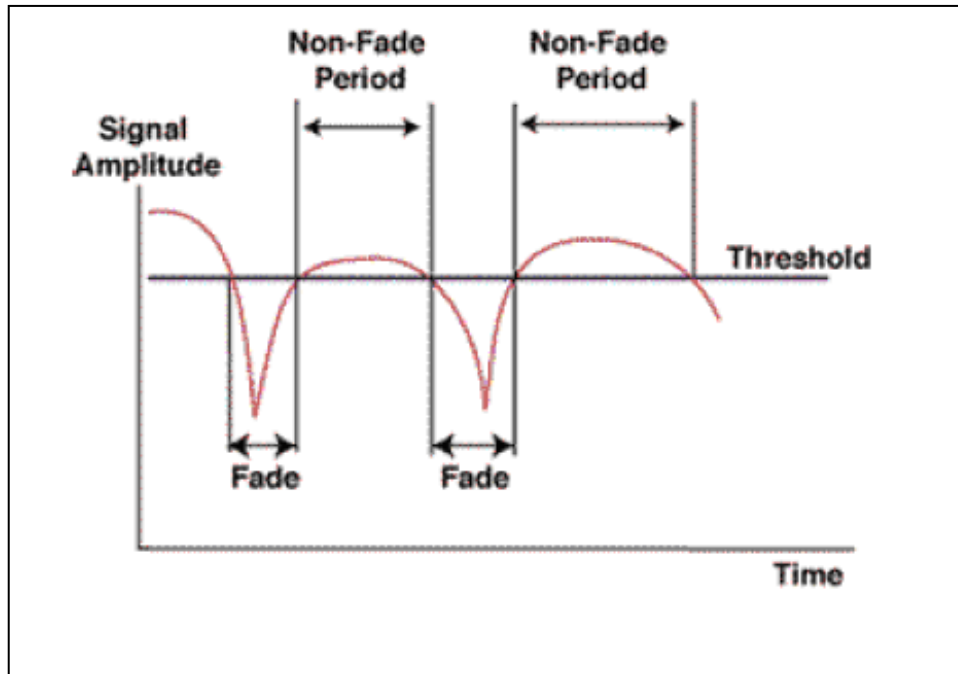


Figure 7. Standing Wave Pattern⁶⁵

If a robot were to progress down a path through a standing wave pattern as depicted in Figure 7, the signal received at different times would have varying amplitudes, with 10 dB to 20 dB (a factor of 10 or 100, respectively) variation not being uncommon in some environments. In the case where the robot stopped in a fade region where the received signal strength (RSS) was low enough, the transmitted video, control, or telemetry may become choppy or drop out. By rolling forward a distance that is 1/4 of a wavelength (at 900 MHz this distance would be approximately four inches), the received signal might return because the robot is now in a non-fade area. For lower frequencies (longer waves), this may entail moving two or three feet, while for higher frequencies (smaller waves), moving a few inches may suffice for improving reception. A similar effect might be observed by moving horizontally or vertically as well.

⁶⁵ Figure 7 from National Institute of Occupational Safety and Health, *Current Status, Knowledge Gaps, and Research Needs Pertaining to Firefighter Radio Communication Systems* (Washington, DC: NIOSH, 2003), 37. <http://www.cdc.gov/niosh/fire/pdfs/FFRCS.pdf> (Accessed June 2, 2007), and Georgia Institute of Technology, Smart Antenna Research Laboratory <http://users.ece.gatech.edu/>.

If instead the controller and robot remain fixed and objects between the controller and robot move in relation to them, this can cause a time-varying loss (gain) in the received signal strength as the signal fluctuates up to 10 dB to 20 dB within a few seconds. Finally, an even larger drop in signal strength may be experienced if the robot moves into an area where a building significantly obstructs the path of the ray; this effect is more commonly known as “shadowing.” Areas behind structures (shadow regions) are particularly subject to this type of loss.

If the modulation scheme used by the robot and control unit covers a wide enough frequency span, they might also see an increase or decrease in received signal level as a result of frequency selective fading; that is, destructive self-interference in some frequencies but not in others. This is particularly troublesome for wide bandwidth, high data rate signals such as real-time video transmissions. Each component – space, time, and frequency – may have an effect on the RSS. One way engineers mitigate this is through diversity techniques. Multiple antennas may be spaced a few inches apart on the transceiver to alleviate spatial fading, and/or the radio may transmit across a range of frequencies to average out the loss. Additional considerations will be discussed at the beginning of Chapter IV.

Rays that pass through a wall create a reflected ray that carries away some of the incident energy. Some of the energy is also imparted to the material in the form of heat (absorption loss). The remainder is transmitted into the air region beyond the wall. The thickness of the wall and its electrical properties will affect the amount of energy transmitted.⁶⁶ The angle of incidence of the ray plays an important part in determining how much of the signal is reflected as opposed to transmitted. In general, the closer the angle of incidence is to grazing the wall, the greater will be the degree of reflection. By contrast, the closer the ray is to normal (perpendicular), the greater the degree of transmission. This effect will be explored further in the sections that consider tunnel and urban canyon propagation.

⁶⁶ Public Safety Wireless Network Program, *In Building/In Tunnel User Considerations: Final* (Washington, DC: PSWN Program, August 2002, A-2.
http://www.safecomprogram.gov/NR/rdonlyres/C45C80A6-9D3D-4A61-8E8C-B30FB71CE850/0/In_Building_In_Tunnel_User_Considerations.pdf (Accessed March 4, 2008).

Diffraction occurs when rays strike the corner of a sharp object or building, changing direction abruptly and continuing in a straight line thereafter. This effect is important to consider as significant path loss can be imparted in turning down a street. When surfaces are substantially uneven or rough, the rays strike the surface and scatter. While scattering is generally lesser in significance than other loss mechanisms, it is included as a component in the tunnel model to be examined, and the significance of scattering can be seen at higher frequencies. In the next section, transmission across flat ground will be considered.

3. Flat Earth Path Gain

The presence of the ground modifies the generation and the propagation of the radio waves so that the received field intensity is ordinarily less than would be expected in free space. The ground acts as a partial reflector and as a partial absorber, and both of these properties affect the distribution of energy in the region above the earth.⁶⁷

This effect can be seen in Figure 8.

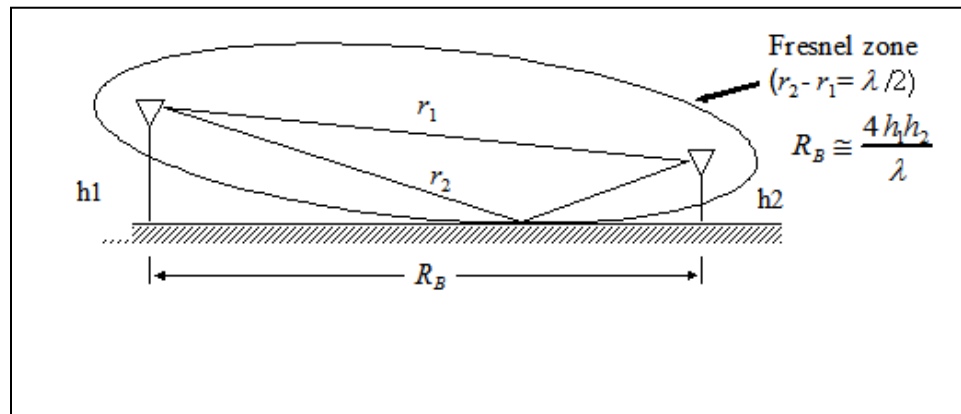


Figure 8. Two Ray Flat Earth Diagram⁶⁸

⁶⁷ Bullington, "Radio Propagation at Frequencies Above 30 Megacycles," 1122.

⁶⁸ Figure 8 adapted from Henry Bertoni, *EL 675 UHF Propagation for Modern Wireless Systems*, (Online course), Chapter 4, Slide 45, <http://eeweb.poly.edu/faculty/bertoni/el675.html> (Accessed March 4, 2008).

Reflections off of objects cause waves to interfere with each other, resulting in dips in signal strength. The effect can be seen in the initial 100 meters of the flat earth path gain curves depicted in Figure 9:

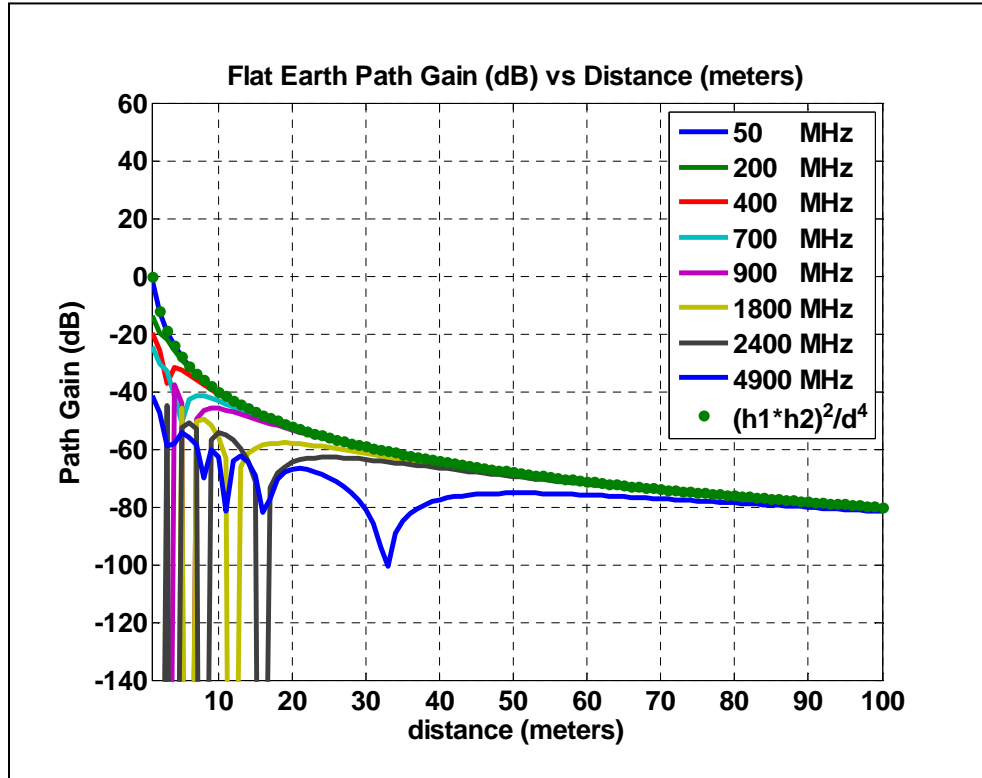


Figure 9. Flat Earth Path Gain for 50 MHz to 4900 MHz

Figure 9 was produced using MATLAB and the flat earth formula in Appendix A. It shows the path gain curves for small (0 dB gain) antennas situated above flat earth at heights of $h_1=1.0$ and $h_2=1.0$ meter respectively. The flat earth path gain exhibits interference-caused variations about free space path gain up to a separation called the break distance R_B . The break distance is the separation distance R between antennas such that the Fresnel ellipse just touches the ground, as shown in Figure 8. The computed Fresnel breakpoints for the respective frequencies plotted above (50MHz to 4900MHz) are 0.6667, 2.6667, 5.3333, 9.3333, 12.0000, 24.0000, 32.0000, and 65.3333 meters. For separations greater than the break distances, the flat earth path gain is characterized by the dependence $(h_1 h_2)^2 / R^4$ for all frequencies, as seen in Figure 9. The $1/R^4$ dependence

for flat earth is much more severe than the $1/R^2$ dependence for free space, and limits communications to much shorter distances, as seen in Figure 10.

It is evident that at relatively low transmitter and receiver heights – as is found in the link between a handheld controller and a robot sitting relatively close to the ground – wide signal variation takes place in the first 70 meters. From the graph it is interesting to note that past the respective breakpoints, the received signal at each frequency decreases at the rate of approximately $1/R^4$. As can be seen in Figure 10, flat earth imparts a significantly greater degree of loss, but is not as frequency-dependent as free space loss by comparison.

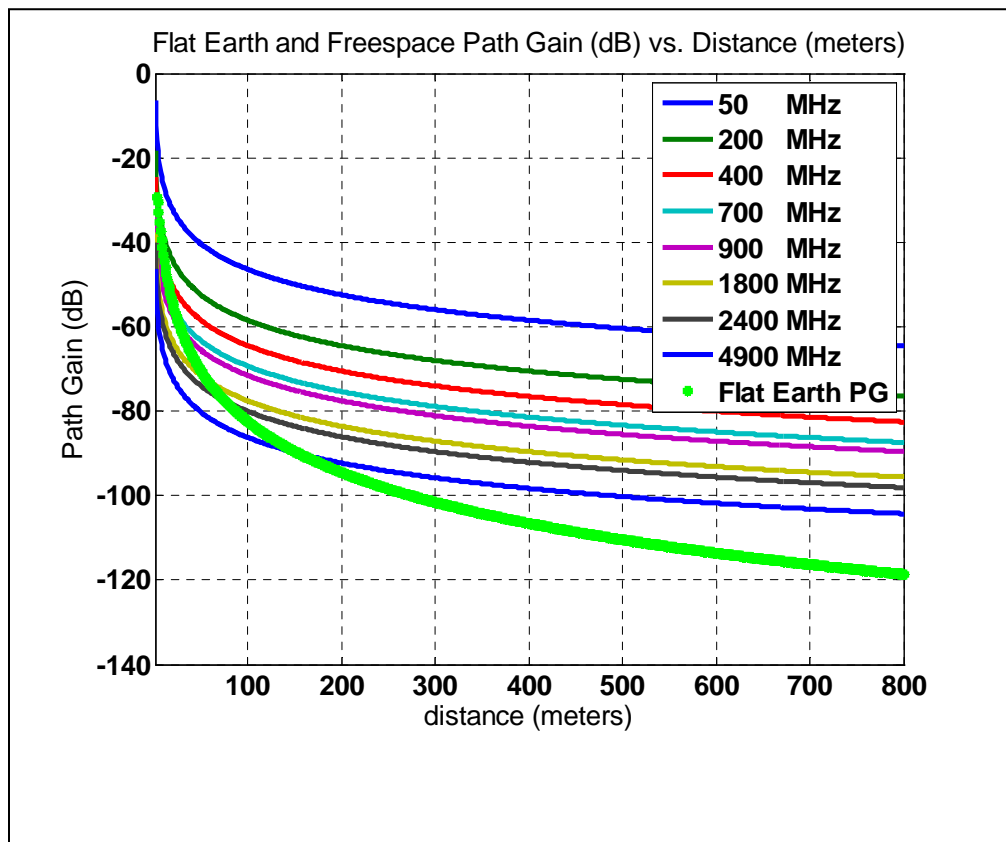


Figure 10. Free Space vs. Flat Earth Path Gain 50 MHz to 4900 MHz

4. Diffraction

Diffraction is an important process by which radio signals travel around a large obstructing object that blocks the direct ray from transmitter to receiver, such as a building. In the ray description of radio waves, a ray from the transmitter illuminates the edge of a corner and gives rise to a fan of rays, one of which reaches the receiver as suggested in Figure 11. In Figure 11 the left-hand frame shows a side view of the simulated scenario, while the right-hand frame shows the attenuation change as the distance h is varied. As h increases, the signal strength decreases. The signal strength if the loss was only due to free-space propagation is represented by the dashed blue line, while the solid line shows the signal strength when the loss due to diffraction is also included.

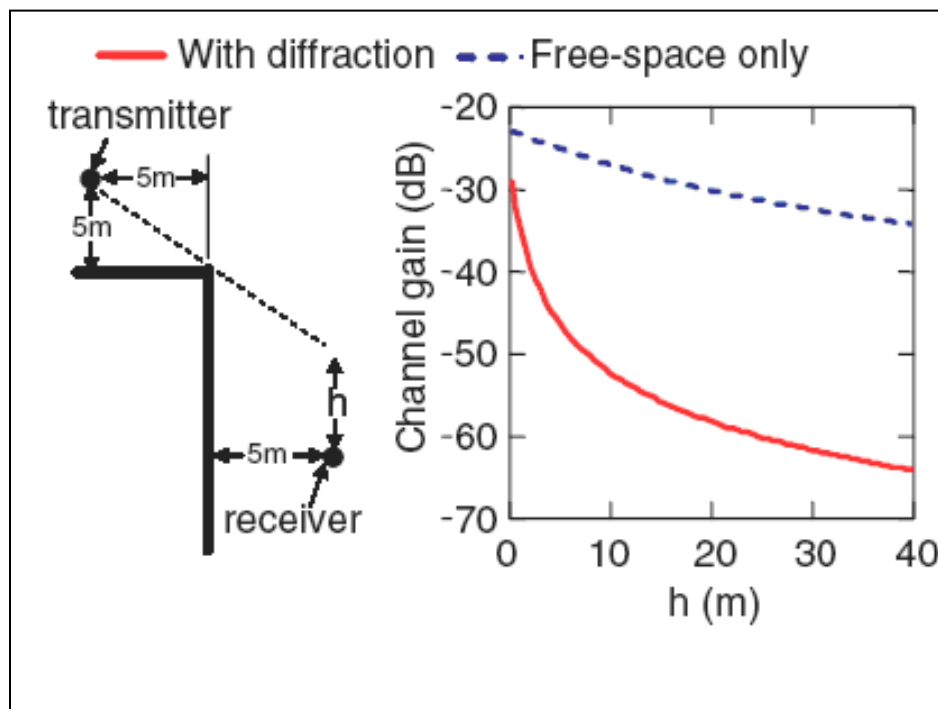


Figure 11. Diffraction around a Corner⁶⁹

⁶⁹ Figure 11 adapted from Sridhara, "Realistic Propagation Simulation of Urban Mesh Networks," 3399.

Figure 11 shows increased attenuation at 2.4 GHz due to diffraction around a corner. In considering the attenuation at a variety of frequencies, as the distance away from the diffraction point increases, the higher frequencies suffer proportionally greater attenuation. The trend is similar to that of free-space path loss, but significantly more severe in the degree of attenuation. In many scenarios, diffraction is an important consideration for determining whether non-line-of-sight (NLOS) communication is possible, and this will be considered in greater depth in Chapter IV, Case Study Three.

5. Tunnels

Recently the wireless field has seen a renewed interest in signal propagation studies in both mine and subway tunnels, following a good deal of study concerning mine communications in the 1970s. In a seminal work on mine tunnel propagation in 1974, Emslie et al. found that in small underground coal tunnels (14ft wide x 7ft high), for frequencies ranging from 200 MHz to 4 GHz, a theoretical model divides radio frequency propagation losses into two zones within the tunnel: a near zone (to the transmitter) and a far zone, with a rough division occurring at the Fresnel breakpoint. Rak and Pechak applied Emslie's work to small cave galleries, postulating that the distance d_B to the breakpoint is given by the minimum of the width or height squared, divided by the wavelength. In the near zone, the loss may be characterized as rapid interference variations about the freespace loss. After the Fresnel breakpoint, the tunnel acts as a waveguide that attenuates the signal amplitude because it is operating below its cutoff frequency. The attenuation is proportional to the frequency squared and inversely proportional to the waveguide (tunnel) dimension cubed; the roughness of the tunnel walls; and the tilt of the tunnel walls (inward slope).⁷⁰ (See Appendix A for formula.)

In a recent paper, Dudley, Lienard, Mahmoud, and Degauque performed a detailed assessment of frequency propagation in a variety of tunnels.⁷¹ They presented data that affirms that when the distance along the length of a tunnel increases, only a few

⁷⁰ Milan Rak and Pavel Pechac, "UHF Propagation in Caves and Subterranean Galleries," *IEEE Transactions on Antennas and Propagation* 55, no. 4 (April 2007): 1134.

⁷¹ D. G. Dudley, M. Lienard, S.F. Mahmoud and P. Degauque, "Wireless Propagation in Tunnels," *IEEE Antennas and Propagation Magazine* 49, no. 2 (April 2007), 11.

low-order modes dominate, and the authors suggest that the modal attenuation model begins at a slightly greater axial distance than prior works indicate. Among the conclusions reached:

- The field can be broken into a near and far zone along the length of the tunnel.
- The near zone field will experience wide and rapid variations due to the interaction of many “modes” of signal propagation. The average over these variations can be approximated by free space loss in the near zone.
- The far zone field will be dominated by the lowest order zone in terms of attenuation.
- The fall-off of the field in the far zone is linear in dB with the slope determined by the attenuation constant of the lowest order mode.
- As frequency increases, the fall-off decreases and the rapid variation of the field persists as the signal travels along the length of the tunnel.⁷²

Based on looking at both circular and rectangular tunnels, they conclude that attenuation is similar for round vs. rectangular tunnels of similar cross sectional area.⁷³ They further conclude, after studying signal propagation in curved tunnels, that “Therefore, there is little to be gained in either a straight or a curved tunnel by increasing the operating frequency beyond the points where the curves flatten.”⁷⁴

For the purposes of this paper we will use Rak and Pechak’s approach, as it is accurate enough for the purpose of this study. Rak and Pechak also make note that the calculation should be taken as approximate, and that a deterministic model would need to be developed for each environment to get more accurate results. Their intent was to approximate UHF radio frequency propagation in small caves for speleology applications. Rak and Pechac applied Emslie’s formula to data they collected in five representative galleries and found a relatively good fit for the frequencies of interest at

⁷² D. G. Dudley, M. Lienard, S.F. Mahmoud and P. Dequaque, “Wireless Propagation in Tunnels,” *IEEE Antennas and Propagation Magazine* 49, no. 2 (April 2007), 22.

⁷³ Ibid., 20.

⁷⁴ Ibid., 23.

446 and 860 MHz. The authors did note that their model does not take conductivity into account, as permittivity dominates in this environment, and state that the model only applies to areas where the wavelength is small compared to the gallery dimensions. Depending on the size of the tunnel, a cutoff frequency exists that precludes effective utilization of lower UHF frequencies for practical operating ranges. The Czech authors also conclude from their study that small galleries (such as the 0.6m x 1.8m cave that they tested) tend to overstate path loss, while large galleries – such as automotive tunnels – may be too optimistic, citing Zhang and Hwang’s “Theory of radio-wave propagation in railway tunnels.” Using Rak and Pechac’s approach, simplified tunnel theory will be applied to two different sized galleries.

a. *Small Tunnel – Cave, Mine, Utility Tunnel*

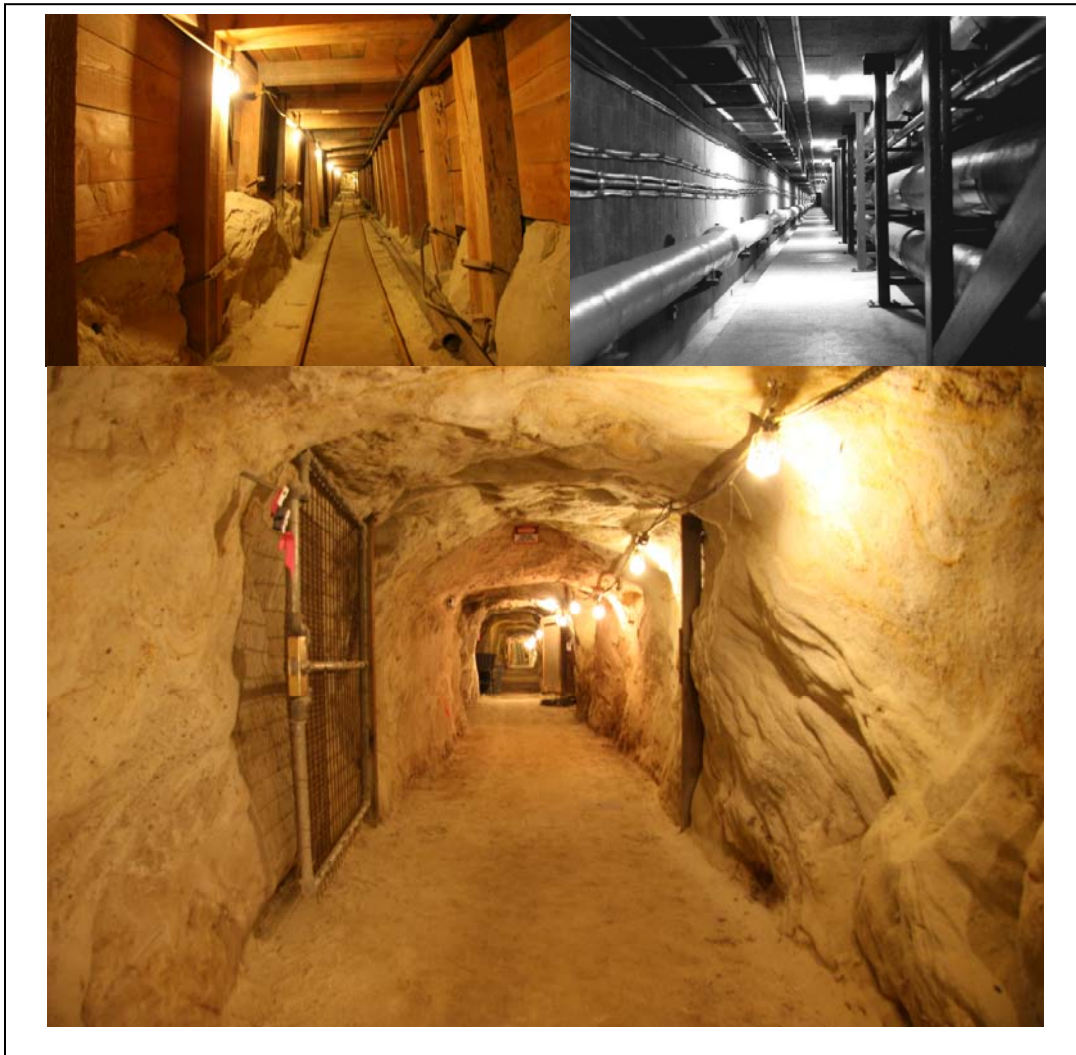


Figure 12. Small Sized Tunnels ^{75,76}

12(a) – Hazel Atlas Mine Tunnel, Black Diamond Mines CA - Top Left

12(b) - Great House Mine Tunnel, Black Diamond Mines CA – Bottom

12(c) – University of Waterloo Service Tunnel – Top Right

Firefighters and other responders encounter many smaller sized tunnels on a regular basis. The tunnels shown in Figure 12 include two abandoned mine tunnels (now used for historical tours) and a university utility tunnel. Some utility tunnels carry

⁷⁵ Photographs 12 (a) and 12 (b) courtesy of Galen Koepke, NIST.

⁷⁶ Figure 12 (c) from <http://matt.wandel.ca/tunnels.html>.

high pressure steam, electrical lines, natural gas lines, etc., and span long distances. Utility emergencies pose challenges for responders to investigate safely. Mine collapses have also been tragically witnessed over the last few years, and robotics are a field of interest for mine rescue.

Data was collected from tests conducted with members of the NIST Electromagnetics Division in the Black Diamond Mine tunnel (top left diagram) near Livermore, CA in March 2007.⁷⁷ Results of the theoretical predictions of the average path gain described previously are compared to the measured data in the following figure:

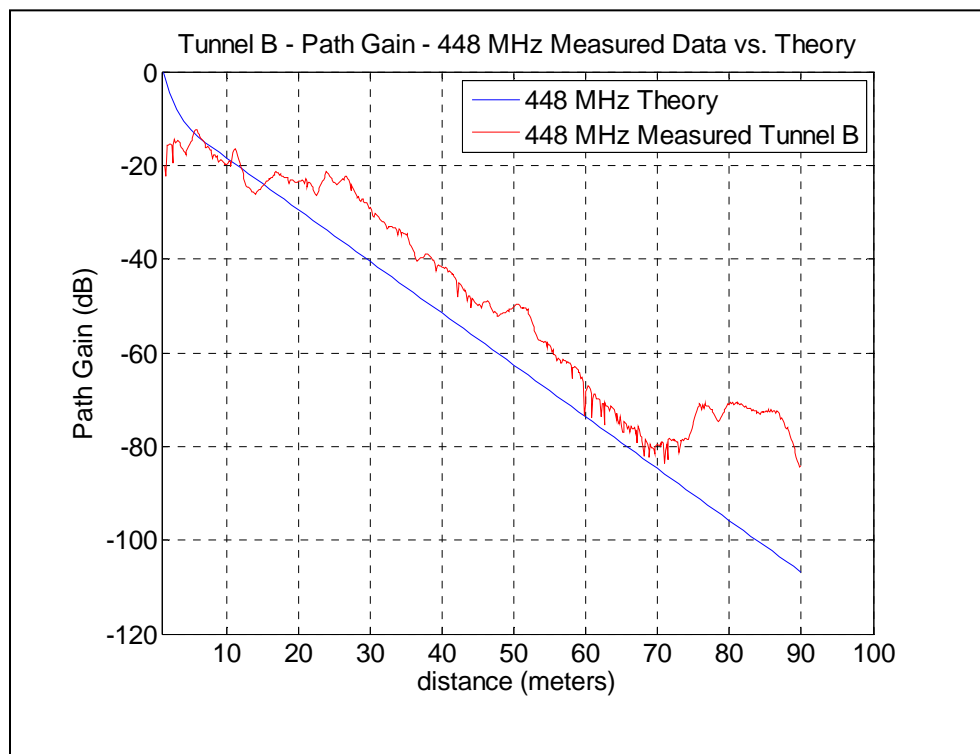


Figure 13. Hazel Atlas Tunnel 448 MHz Path Gain: Measured Data vs. Theory

The theory in Figure 13 can be seen to closely match the observed data for the 448 MHz carrier frequency. However, when test data were compared to theory for frequencies of 220 MHz and below, the theoretical curve was much less suitable for predicting path loss.

⁷⁷ Remley and others, *Measurements to Support Modulated-Signal Radio Transmissions for the Public-Safety Sector*, NIST Technical Note 1546, (Washington, DC: U.S. Department of Commerce, Electromagnetics Division of NIST, October 2007), 74.

The path loss was also significantly greater due to the larger size of the wave in relation to the size of the gallery. The net effect of the model was to overstate loss, as was anticipated by Rak and Pechac.

Figure 14 presents the path gain computed using the Rak and Pechac model on a 14ft x 7ft rough walled coal tunnel using 0.1m for roughness and 1 degree for tilt of the walls:

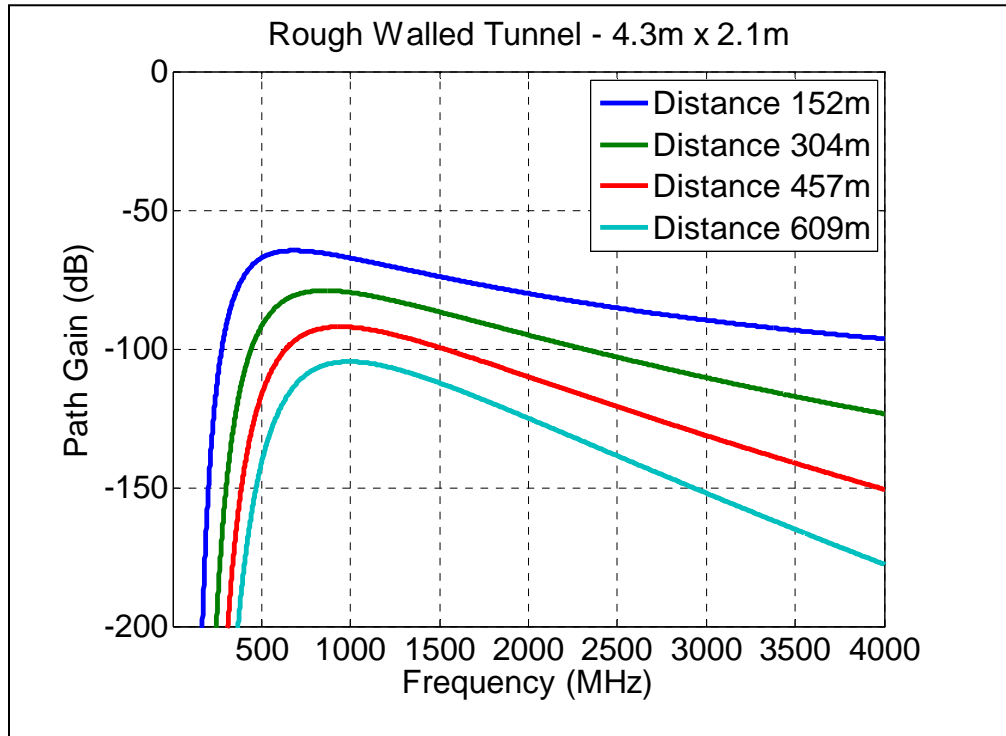


Figure 14. Theoretical Path Gain for Rough Walled Tunnel

As the distance increases, the higher frequencies experience progressively greater attenuation in a rough walled tunnel. Removing wall tilt and roughness factors in the calculation demonstrates the effect on attenuation as a function of frequency for a smooth walled, rectangular tunnel of the same 14ft x 7ft dimensions. The average path gain results for these calculations are depicted in Figure 15, which are seen to be somewhat different at higher frequencies from those of Figure 14. However, both sets of curves indicate the highest value of path gain is obtained for frequencies in the range from about 600 MHz to 1 GHz.

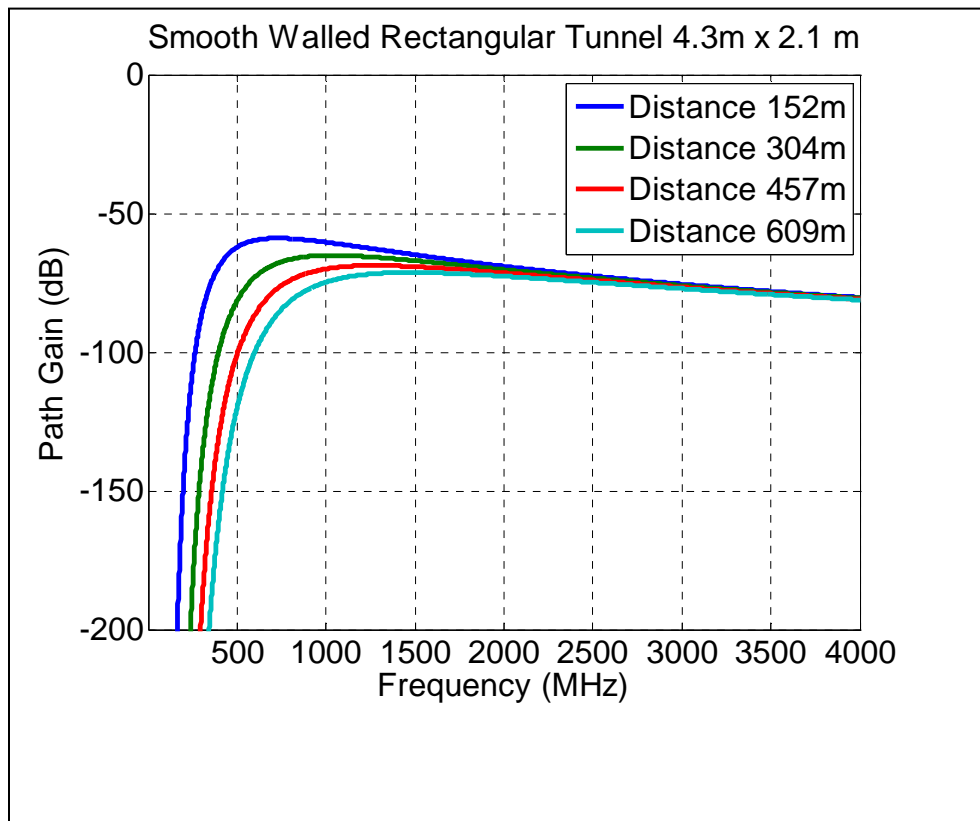


Figure 15. Theoretical Path Gain for Smooth Walled Tunnel

An interesting effect seen in both graphs is that the optimal frequency - based on least amount of path loss - increases slightly with increasing distance. The effect is much more pronounced in rough walled tunnels.

b. Medium Dimension Tunnel – Under River Subway and Automobile



Figure 16. Subway Tunnels^{78,79}

Figure 16(a): (Left) Arch-Shaped Tunnel

Figure 16(b): (Right) Rectangular Tunnel

Notice in Figures 16(a) and 16(b) the walls that line the tunnel contain numerous conduits and additional irregularities that cause extra scattering and attenuation of radio waves. While the presence of long metallic rails and pipes may help certain frequencies (most probably the lower frequencies), the majority of the frequencies will suffer additional losses. Figure 16(a) shows the arch-shape that is associated with some under-river tunnels and Figure 16(b) shows the rectangular shape that is consistent with cut-and-cover construction techniques. For the purposes of this discussion, our focus will be on tunnels such as shown in Figure 16(a) as they pose significant challenges to responders.

In considering tunnel propagation effects, signal measurements taken in the Massif Tunnel will be examined in the following section as the results offer a useful

⁷⁸ Photograph from www.undercity.org/photos/1Gallery/SubwayA002.htm, (Accessed March 21, 2008).

⁷⁹ Photograph from <http://www.mta.info/nyct/facts/ffenvironment.htm>, (Accessed March 21, 2008).

case study for assessing our model. Afterwards, propagation in a curved tunnel will be considered for the additional path loss that the curved section contributes.

c. Massif Tunnel (France) Test Results

Lienard and Degauque conducted wireless propagation testing in the Massif Central Tunnel (south-central France) in November 2005.⁸⁰ The dimensions and shape of the tunnel are shown in Figure 17, accompanied by the results for 450, 900, 2100, and 10,000 MHz received signal (dBm) measurements.

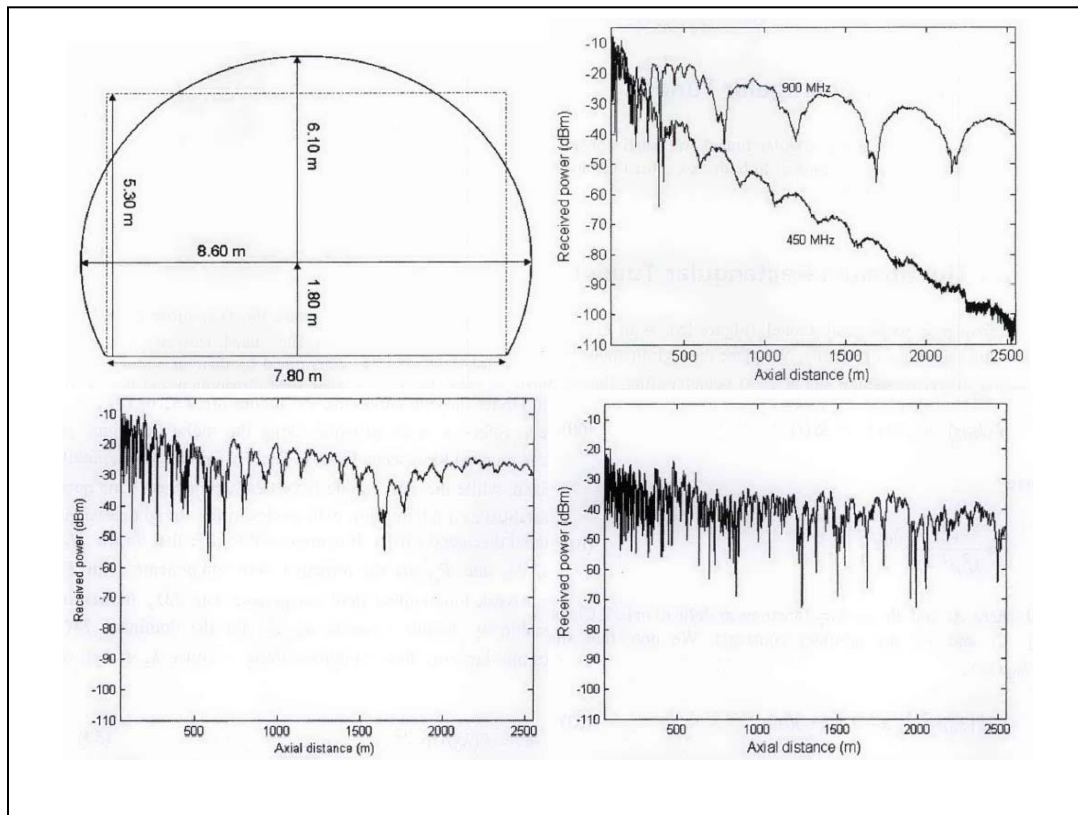


Figure 17. Massif Tunnel Path Gain Measurements

17(a) - Tunnel Dimensions (Top Left)

17(b) - 450 and 900 MHz Received Power (dBm) (Top Right)

17(c) - 2.1 GHz Received Power (dBm) (Bottom Left)

17(d) - 10 GHz Received Power (dBm) (Bottom Right)

⁸⁰ Figure 17 includes D. G. Dudley, "Wireless Propagation in Tunnels," Figures 18-20, 20-21.

For comparison, the theoretical predictions of the average fields are shown in Figure 18, taking into account the power transmitted and antenna gain.

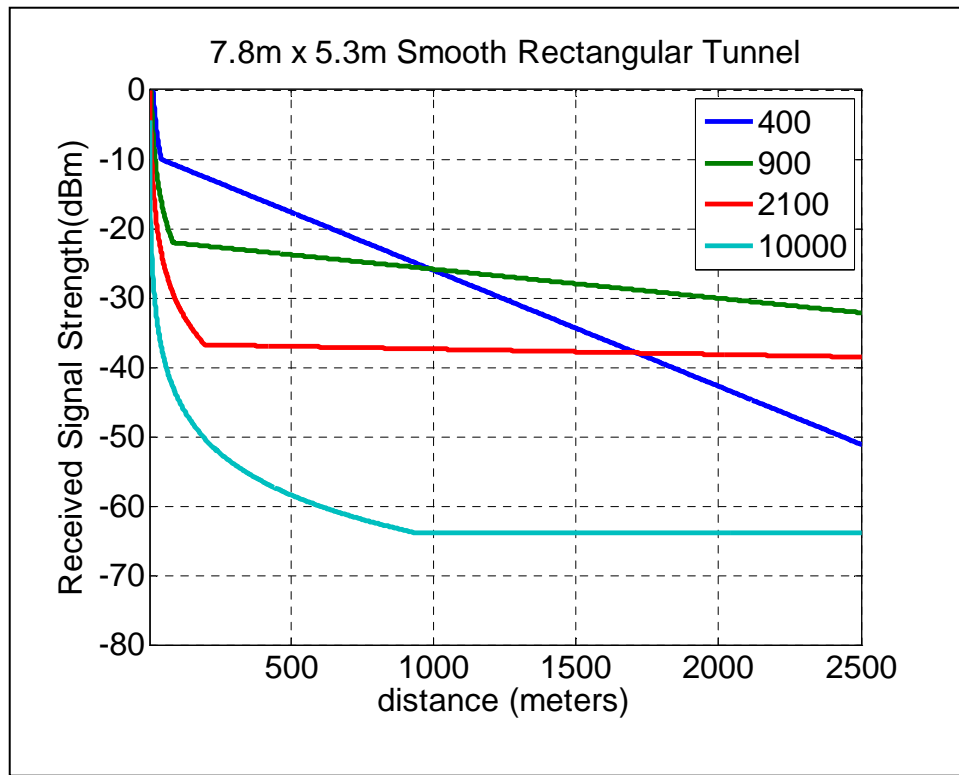


Figure 18. Theoretical Path Gain for Massif Tunnel

In Figure 18, the theoretical path gain is computed for an approximation of the Massif Tunnel using received power (dBm) for a 7.8m wide x 5.3m high, smooth tunnel with $h=0.01$ (roughness) and $\theta=0$ degrees (tilt). By comparison, the measured data from the Massif Tunnel testing and the model provide fairly close agreement at 900 MHz and 2100 MHz in the study. The 400 MHz theoretical path loss was understated by the theory, and the 10 GHz signal overstated the loss. The propagation is significantly better than $1/d^2$ for 900 and 2100 MHz.

d. Curvature in a Tunnel

In a tunnel with a curve, the curved part adds an additional amount of attenuation over and above that which is caused by a straight tunnel of the same total length. The loss in the tunnel up to the end of line of sight is dependent upon the distance

in comparison to the Fresnel breakpoint distance. The general trend is for attenuation to decrease with increasing frequency. Working from the three papers mentioned in Appendix A, an approximate expression of the attenuation in the curved part of the tunnel is presented in Figure 19 (Refer to Appendix A for derivation of the attenuation due to the curve).

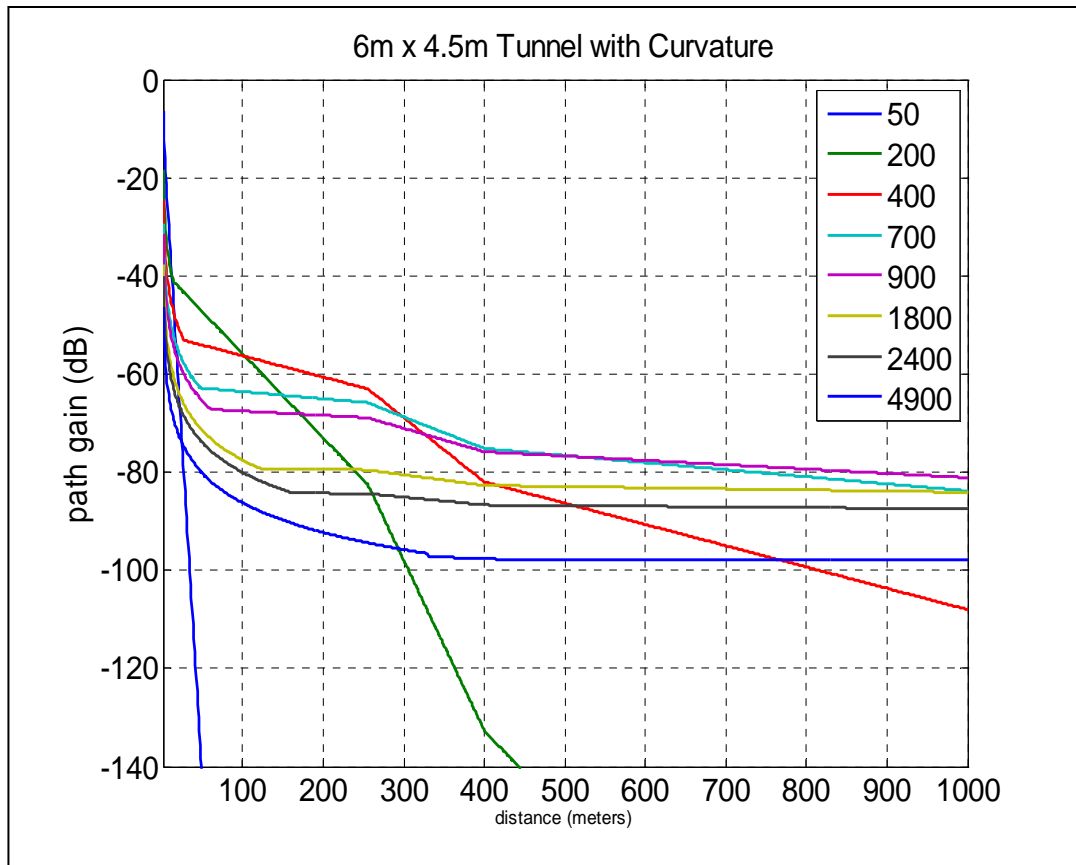


Figure 19. Attenuation in a Tunnel with Curvature

Figure 19 shows a model that takes into account free space loss up to each frequency's Fresnel breakpoint, then straight tunnel loss up to the end of the line-of-sight component of the tunnel. In this scenario, the tunnel is straight until 200 m, and then begins a turn with radius of curvature equal to 500 m. The line-of-sight component continues until about 55 m into the turn (total distance from the transmitter of 255 m). The curved section ends at a total distance of 400 m and then continues with straight tunnel loss up to 1000 m. Tunnel wall roughness is taken as 0.1 m, and no tilt is used in

the calculation. The model is in general agreement with other works that show attenuation decreases proportionately compared to increasing frequency, and that the effect is greater in bends having a smaller radius of curvature.⁸¹

6. Propagation in Urban Canyons

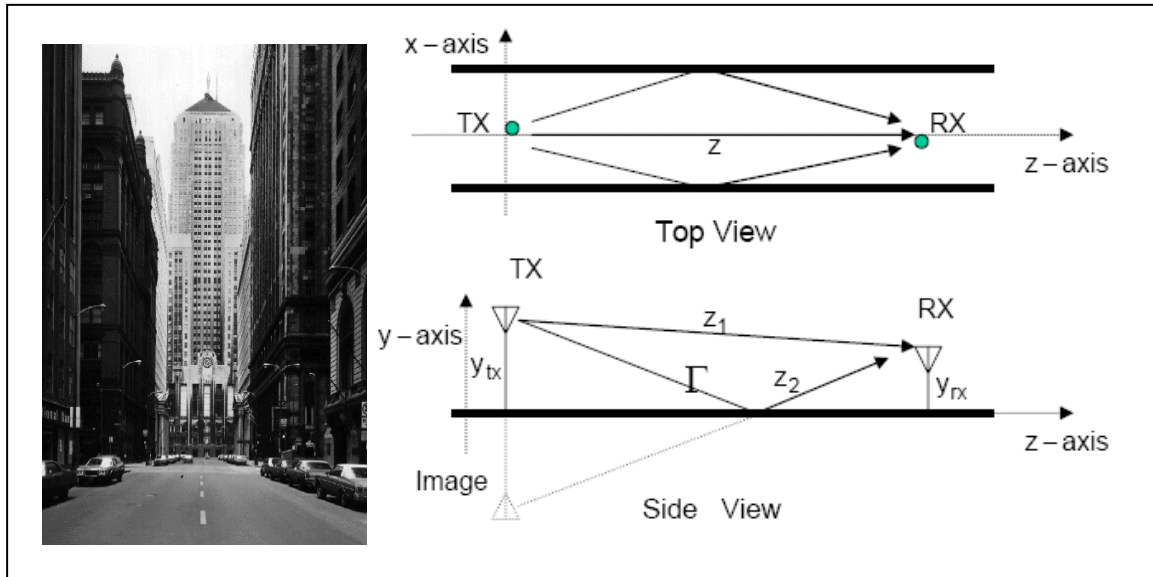


Figure 20. Urban Canyon Effect^{82, 83}

Figure 20(a) on left shows an Urban Canyon.

Figure 20(b) on right shows the Top and Side Views of how radio waves reflect off both the ground and the building walls in propagating down a street canyon.

Since one of the more important applications for robotics may be to investigate potential CBRNE incidents as well as unstable buildings and utility emergencies in large cities, the propagation characteristics in a downtown high-rise area such as that shown in Figure 20(a) are well worth considering. In 2003, Lee and Bertoni provided a study of path loss in tunnels and urban canyons with cross junctions using a modeling approach similar to that for tunnels, and also characterized the coupling loss into the intersecting

⁸¹ D. G. Dudley, "Wireless Propagation in Tunnels," 23.

⁸² Photo by Barbara Crane, "View Down LaSalle Street Canyon," <http://www.ci.chi.il.us/Landmarks/B/BoardTrade2.html> (Accessed February 3, 2008).

⁸³ Figure 20 from Jeho Lee and Henry Bertoni, "Coupling at Cross, T, and L Junctions in Tunnels and Urban Street Canyons," *IEEE Transactions on Antennas and Propagation*, 51, no. 5 (May 2003): 926.

street.⁸⁴ Figure 21 shows a computed path gain profile for propagation along a 5-m wide street to show the frequency selective effect along narrow streets. The transmitter is 1.5-m high and a receiver (robot) is one-half-m high – essentially a robot operation down a long narrow alley.

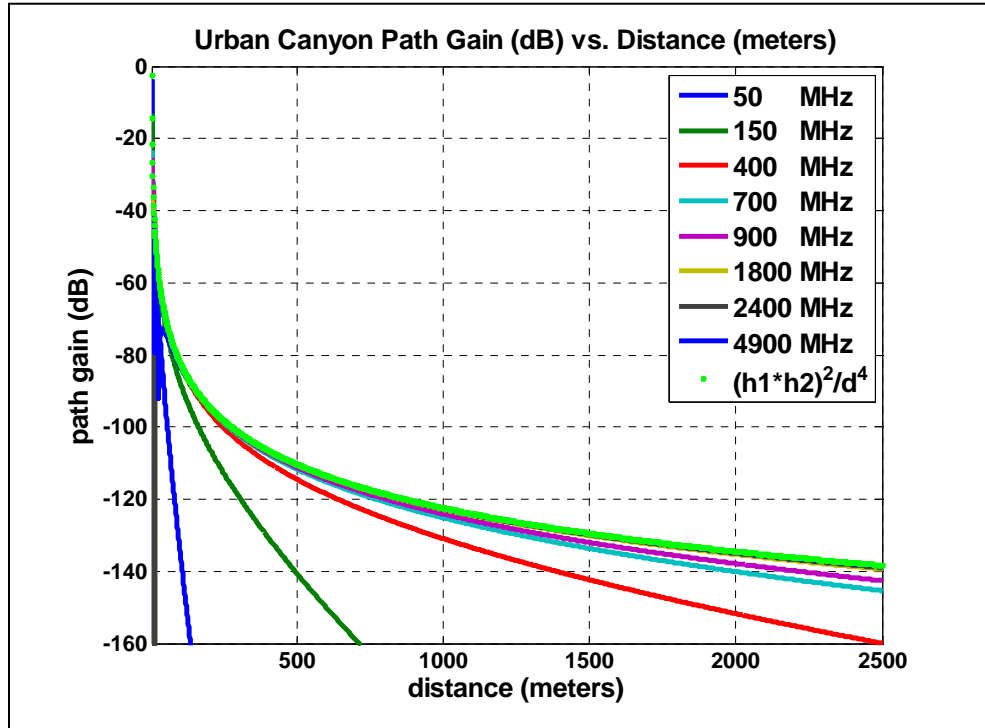


Figure 21. Urban Canyon Path Gain

Figure 21 follows the form of the flat earth model that was presented earlier. As the signals progress further along the street they experience attenuation from the canyon walls, and the received signals at lower frequencies tend to be much weaker than the flat earth approximation.

When the robot turns a corner and proceeds some distance down the street, propagation between the robot and the control unit involves diffraction of the radio signal by the four building corners at the intersection. Figure 22 is a plot of the path gain as the robot moves down a 30-m main street, turns into a side street and continues down the

⁸⁴ Jeho Lee and Henry Bertoni, “Coupling at Cross, T, and L Junctions in Tunnels and Urban Street Canyons,” *IEEE Transactions on Antennas and Propagation*, 51, no. 5 (May 2003): 926.

side street. For this plot, the antenna heights are $h_1 = 10$ m, $h_2 = 2$ m, and the street width is 30 m. For comparison, the measured path gain at 900 MHz on such a route is plotted in Figure 22(a).⁸⁵ Note that the distance scale in Figure 22 is logarithmic, so that large distances appear compressed. It can be seen from these figures that there is a significant reduction in the received signal (some 40 dB) when the robot turns the corner. The model presented is somewhat pessimistic as compared to the path loss from actual measurements that were taken on a Manhattan, NY street in Figure 22(b). However, the formula is useful as a conservative planning tool to ensure a robust wireless link.

⁸⁵ Jeho Lee and Henry Bertoni, "Coupling at Cross, T, and L Junctions in Tunnels and Urban Street Canyons," *IEEE Transactions on Antennas and Propagation*, 51, no. 5 (May 2003): 933, and Vinko Erceg, A.J. Rustako, Jr., R.S. Roman, "Diffraction Around Corners and Its Effects on the Microcell Coverage Area in Urban and Suburban Environment at 900 MHz, 2 GHz and 6 GHz" (*Global Telecommunications Conference*, 1994), 52-57.

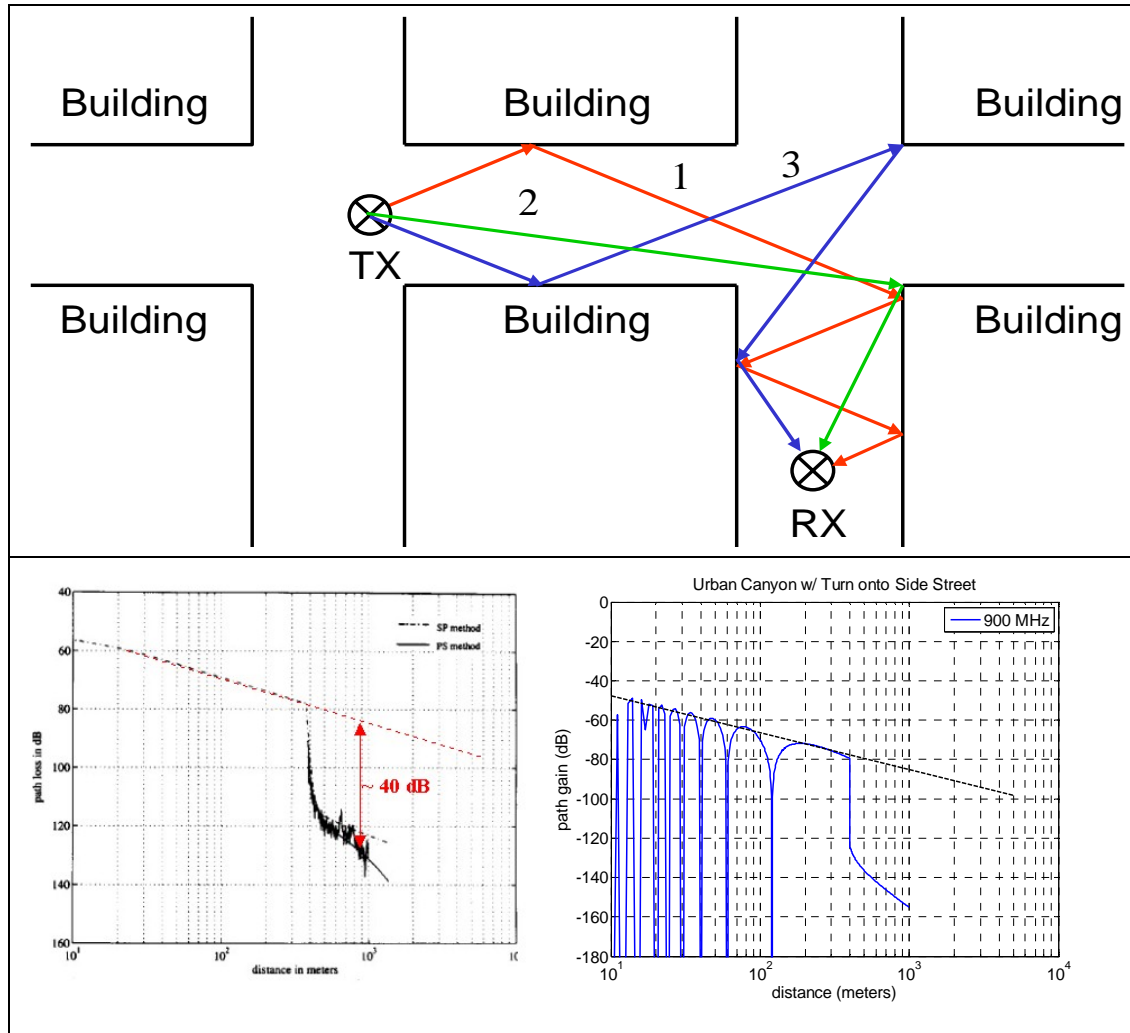


Figure 22. Urban Canyon with Turn onto Side Street ^{86,87}

Figure 22(a) on top shows diffraction of rays onto a side street in an urban canyon.

Figure 22(b) on the lower left shows the measured path loss from a 900 MHz signal transmitted in an urban canyon with the receiver on a side street.

Figure 22(c) on right shows the computed path gain based on the formula given in Appendix A.

⁸⁶ Figure 22(a) from Bertoni, "EL 675 UHF Propagation for Modern Wireless Systems," Chapter 13, Slide 15.

⁸⁷ Figure 22(b) from Lee "Junctions in Tunnels and Urban Street Canyons," 926 and Erceg "Diffraction round Corners and Its Effects on the Microcell Coverage Area in Urban and Suburban Environment at 900 MHz, 2 GHz and 6 GHz," 52-57.

7. Buildings: Communications Inside, Outside-to-Inside, and Around Structures

Communications between a controller and robot in and around a building environment is a complicated issue. Building construction involves many layers of materials with differing propagation characteristics. As has been seen with the other environments studied thus far, the geometry of the structure also plays an important role in determining the ultimate operating range. The following is a summation of the important general characteristics effects from the study referenced in *UHF Propagation for Modern Wireless Systems* (see footnote 88; also, additional information included in Appendix B).

- Wall and floor loss increases somewhat with frequency.
 - Plaster board walls ~ 3 - 6 dB, wood floors ~ 9 dB
 - Concrete walls ~ 7 dB, concrete floors ~ 10 - 20 dB
- Variation of signal attenuation with respect to distance.
 - Some guiding in hallways reduces loss compared with free space.
 - Excess loss due to propagation through walls gives exponential decrease with distance.
- Propagation between floors may take diffraction paths when floor loss is high.
- Blockage by people moving close to one end of link results in 20 dB fades.⁸⁸

The angle of incidence plays an important role in determining the amount of transmission verses reflection. The following example of wall loss offered by Sridhara and Bohacek, and depicted in Figure 23, shows the effect of the angle of the path linking the transmitter and receiver through a wall. The angle effect can be of greater significance than the actual building materials.

⁸⁸ Bertoni, EL 675, *UHF Propagation for Modern Wireless Systems*, Chapter 6, Slide 29).

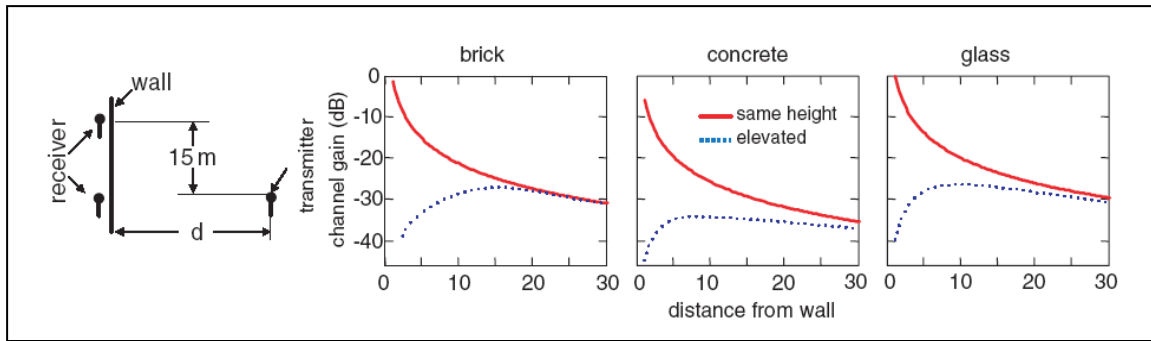


Figure 23. Transmission through a Wall⁸⁹

Figure 23 shows in the left hand frame a side-view of the simulated scenario of a transmitter moving away from the wall, with a receiver placed at two different heights. The three graphs to the right of it show the attenuation of the signal when transmitted through walls made of three different materials.

In a recent effort to develop a simplified approach to calculating path loss involving an indoor/outdoor interface, based on four general categories of building construction, Bacon and Thomas stated, “Losses due to propagation into, within, or out of buildings can be added in dB to the basic transmission loss predicted for longer paths not taking the buildings into account. Propagation within buildings can be characterised by a horizontal attenuation rate in dB/m, thus making indoor losses proportional to horizontal indoor distance.”⁹⁰ The authors note that the model is not suitable at present for paths between floors at substantially different heights in different buildings or for high-angle paths.

Bertoni presented an example of three paths for signal travel between lower floors and upper floors. A side view of a narrow building is shown in Figure 24, together with the potential ray paths. The figure also shows measured path gain for transmitter locations on different floors, and compares the path gain to that computed for the

⁸⁹ Figure 23 from Sridhara, “Realistic Propagation Simulation of Urban Mesh Networks,” *r*: Figure 4, 3397.

⁹⁰ David Bacon and Nick Thomas, “Simulation and Modelling of Propagation Paths Involving the Indoor/Outdoor Interface” (*Proceedings of the International Symposium on Advanced Radio Technologies*, Boulder, CO, 2007), 43.

different ray paths. The results indicate that the strongest signal may be accounted for by rays that exit a building via a window and re-enter at another floor when the transmitter and receiver are separated by a number of floors.

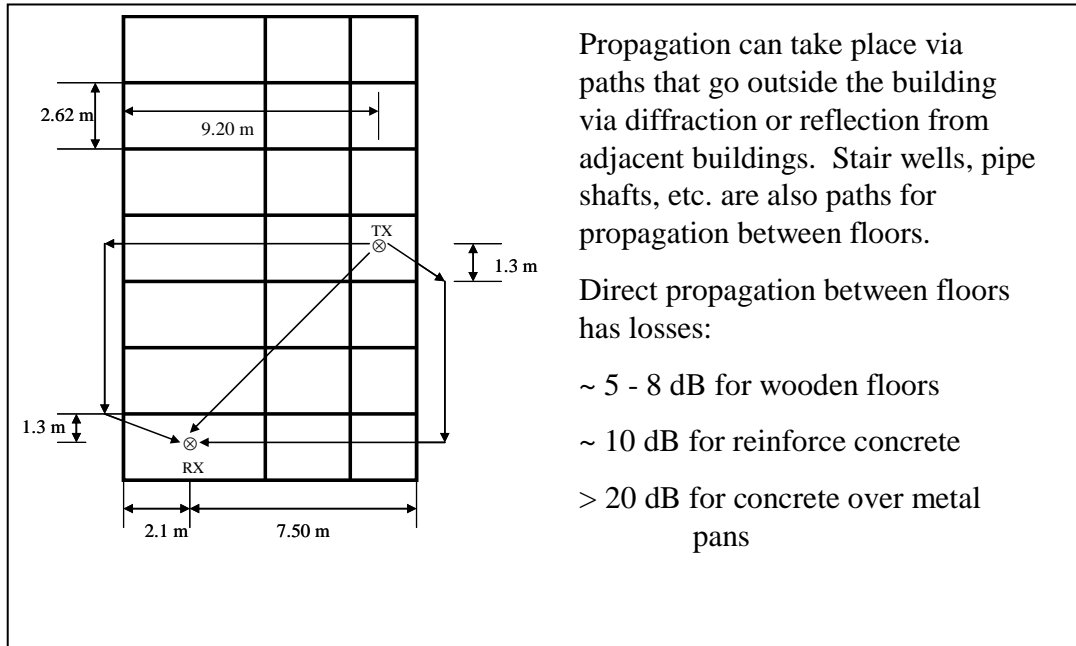


Figure 24. Propagation Paths and Path Loss between Floors of a Building⁹¹

The combined effect of radio waves traveling through walls of different materials and via many different paths into the building is referred to as building penetration loss. In a seminal study, Davidson et al. looked at the frequency selectivity of building penetration loss from numerous studies that had been done across a range of frequencies. Figure 25 shows the summary graph that Davidson et al. provided, along with three additional path loss studies by Hoppe et al., Aguirre, and Remley et al. Also included is an estimated visual data fit to show the trend for building penetration loss at frequencies ranging to 10 GHz. The lines that are in color have been added to the original curve and are approximations based on an interpretation of the data presented in the selected works. While the approximations are a best effort in looking at a large scale trend, the reader should reference the respective works for a finer resolution data fit.

⁹¹ Figure 24 from Bertoni, EL 675 *UHF Propagation for Modern Wireless Systems*, Chapter 13, Slide 55.

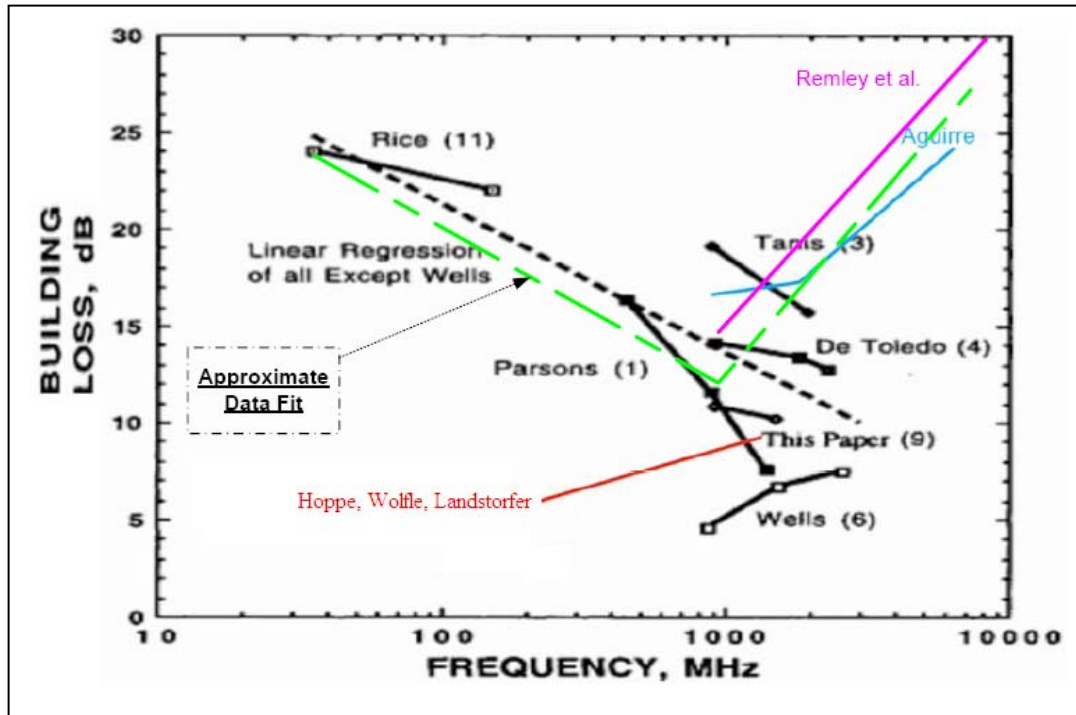


Figure 25. Building Penetration Loss⁹²

Figure 25 shows an overall decrease in building penetration loss as frequency increases up to about 1 GHz. Above 1 GHz the loss increases. While the results presented are only estimated for the added papers, the ‘V’ shaped trend is distinct and useful for drawing conclusions about the optimal frequency range for sending robots from a street into a building, and/or sending information from inside to outside. While this feature will not be explored further in the scenarios in Chapter IV, the results from this compilation of work are relevant for considering general frequencies for operation and will therefore be included along with other summary data.

⁹² Figure 25 adapted from A. Davidson and C. Hill, “Measurement of Building Penetration into Medium Buildings at 900 and 1500 MHz,” *IEEE Transactions on Vehicular Technology* 46, no. 1 (February 1997): 167, Figure 9, and private discussion with Dr. Henry Bertoni, (Professor Emeritus Polytechnic University), Interview with author, Brooklyn, NY February 28, 2008 concerning the addition of R. Hoppe, G. Wolfle and F.M. Landstorfer, “Measurement of Building Penetration Loss and Propagation Models for Radio Transmission into Buildings,” In *IEEE 5th Vehicular Technology Conference*, (Amsterdam: September 19-22, 1999), vol. 4, 2300, Table 2, and S. Aguirre, L.H. Loew and Lo Yeh, “Radio Propagation into Buildings at 912, 1920, and 5990 MHz using Microcells” IN *3rd Annual International Conference on Universal Personal Communications*, (San Diego, CA: September 27 – October 1, 1994), 134, Figure 8, and Kate A. Remley and others, *Measurements to Support Modulated-Signal Radio Transmission for the Public-Safety Sector* 74.

8. Additional Factors

Emergency response takes place at all hours of the day and in all weather conditions. A study on the use of 2.4 GHz and 5 GHz WLAN cards in a small tunnel 1.5m wide by 2m high with a fire between the transmitter and receiver revealed the following:

- Technologies using the 2.4 GHz frequency band achieve a higher communication range than technologies using the 5 GHz band in the tunnel system.
- Fire and smoke do not severely affect the communication performance of devices operating in the 2.4 GHz band.
- Vapor reduces the transmission quality by decreasing throughput and range and increasing jitter.⁹³

D. RADIO ENVIRONMENT: CAPACITY, INTERFERENCE, AND PROTOCOLS

The radio environment – mentioned earlier as one of the external factors in the modified TAM – refers to the rules (protocols) that govern how information is transmitted. In the prior section, path loss was discussed for various environments. However, other factors contribute to how far one can effectively transmit a signal. In trying to determine the distance to send a robot where a minimally acceptable video signal might be received, it is necessary to look at the following components: link margin and capacity.

1. Link Margin

A link margin (a.k.a. link budget) is a summation of the all gains and losses that may affect a signal as it travels from transmitter to receiver. Performing a link analysis is the analog to balancing one's checkbook; the sum of the credits (gains) and debits

⁹³ Philipp Hofmann and others, "Are IEEE 802 Wireless Technologies Suited for Firefighters?" (*12th European Wireless Conference 2006*, Athens, Greece, April 2-5, 2006), 5.
<http://www.bettstetter.com/publications/hofmann-2006-ew-fire.pdf> (Accessed June 2, 2007).

(losses) must be greater than zero or else problems begin to occur from insufficient funds in the bank account (unintelligible voice or dropped data packets). A wireless communication link will operate over a specific range based on a transmit-to-receiver power budget and might be represented as follows:

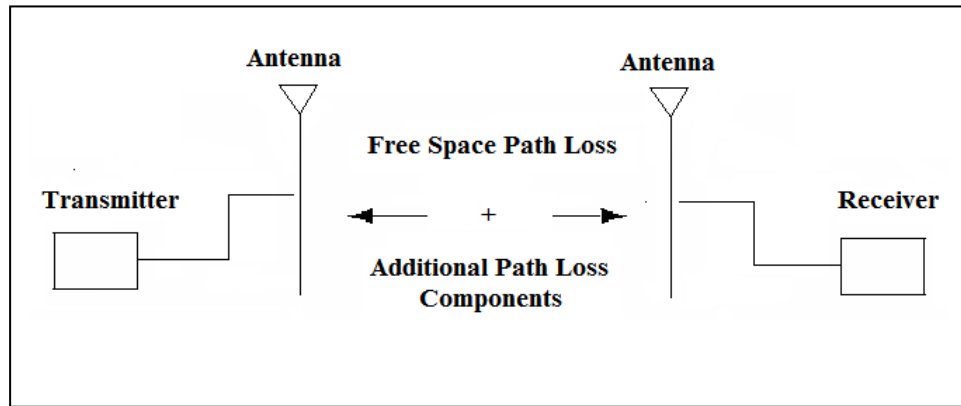


Figure 26. Wireless Transmission Link

In considering a successful communications link, the following concepts apply:

- The transmitter supplies the power for sending a wireless signal from an antenna. The greater the transmitted power, the further the receiver can be placed while still being able to “make sense” of the signal. The relationship is not linear – meaning that as more power is applied, less benefit in terms of distance is gained. Other factors such as battery weight also limit the attractiveness of using increased power to extend a link.
- Additional gains can be realized through the type of antenna used for either transmission or reception. Most antennas currently used with robotics do not provide significant gains because they are designed to both transmit and receive in all directions (omni-directional), and are generally as small as practical to minimize obstruction and decrease weight. An antenna that focuses a beam in a particular direction – called a directional antenna – would increase either the received or transmitted signal strength in that particular direction and introduce a gain to the equation. However,

if a robot turns sideways the received signal strength will drop dramatically, and it will probably lose its radio link unless its antenna moves as well.

- The receiver must be able to decode the signal that it receives. The better the quality of the receiver, the better its ability to discriminate a transmitted signal at a lower level as compared to lesser quality receivers.
- The signal-to-noise ratio, SNR, is the ratio of the transmitted signal power to the ambient background noise that is always present in any communication link.
- The cables that connect the antenna with the transmitter and receiver may create some loss, although for robotics this loss is usually negligible.
- The distance the transmitter is from the receiver (robot) might cause the predominant path loss while the condition of the environment between the transmitter and receiver will also decrease the received signal strength in a variety of ways, as has been already detailed earlier in this chapter.⁹⁴

A link budget is the computation of the whole transmission chain and is calculated by the equation in Figure 27 when all factors are expressed using the dB scale.

⁹⁴ Time varying losses - For instance, depending on the transmission frequency the time varying amount of particulates (such those caused by a fire) in the communication channel could cause time varying channel losses. The time varying changes in the fixed channel losses are taken as a whole to be the “fade margin.”

Minimum Transmitter (Tx) Power = (Tx gains – Tx losses) + Minimum Power to Receive (Rx) + (Receiver gains - Receiver losses) - Fixed Communication Path Loss - Variable Communication Path Loss	Excess Link Margin (ELM) = (Power Tx + Gain Tx – Cable Loss Tx) - Total Path Loss – (Power Rx – Gain Rx + Cable Loss Rx)
---	--

Figure 27. Excess Link Margin Equation⁹⁵

Figure 27(a) (Left) – Minimum Transmitter Power

Figure 27(b) (Right) – Excess Link Margin

Recall that the communication path loss is the inverse of the path gain expressed in dB. The difference between the received signal strength and the minimum receiver sensitivity is important for determining if a signal will be sufficient. It is sometimes referred to as the link margin, fade margin, or excess path loss. In order for the link to work, the sum must be greater than 0. The balance remaining gives the “excess margin” of the system. The term that will be used for the purposes of this paper will be the excess link margin (ELM).

2. Capacity

The next major consideration is the amount of data that can be sent. In general, received RF power and bandwidth effectively place an upper bound on the capacity of a communications link. For analog systems, such as FM voice transmission or standard AM television, noise causes a degradation of the voice quality or image. As an example, acceptable quality FM voice requires a signal-to-noise ratio (SNR) of 10 dB or better; that is, the signal must be at least 10 times stronger than the background noise. For digital

⁹⁵ Figure 27(a) equation based on Rob Flickenger and others, *Wireless Networking in the Developing World* (Hacker Friendly LLC, January 2006), Chapter 4, 69, <http://wndw.net/download.html#english> (Accessed March 4, 2008).

systems, the effect of background noise is to give an upper limit to the data rate that can be transmitted. The upper theoretical limit is given by Shannon's Channel Capacity theorem in Figure 28:

$$C = B \times \log_2 (1 + S/N)$$

C=capacity (bits/sec)
 B=bandwidth (Hz)
 S= Received Signal Power (Watts)
 N=Noise Power (Watts)

Figure 28. Shannon's Channel Capacity Theorem

The capacity represented by this equation is the upper limit, and in reality the capacity would be difficult to attain using real hardware. An operator may notice degraded imagery on the video display of the OCU. As an example, consider the display of black and white imagery in Figure 29.

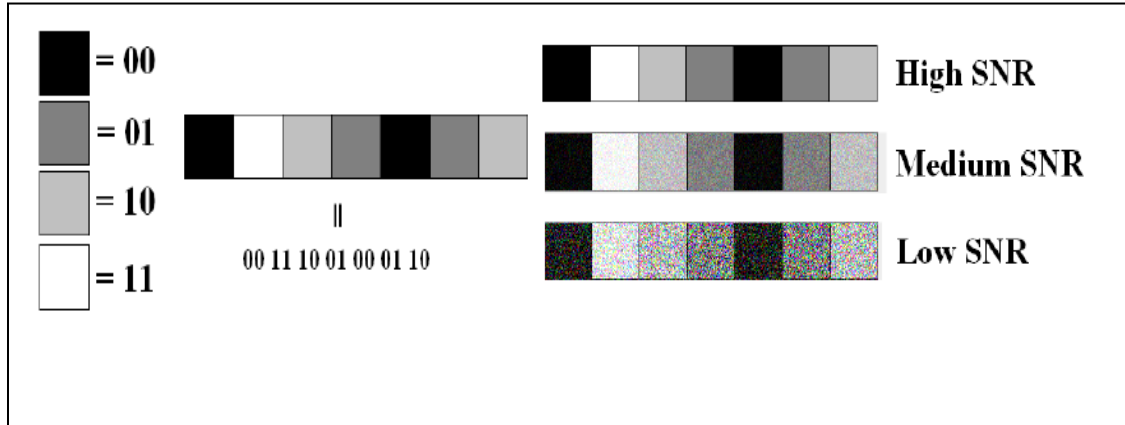


Figure 29. Signal to Noise Ratio (SNR) From [96]

Notice these distinctions from Figure 29:

- The upper sequence was sent over the low noise environment that allows a high SNR channel. The sequence is very clear and the information is easily detected.

- The middle sequence has medium SNR, but there's still no problem detecting the information without error.
- The lower sequence has a low SNR and the signals become difficult to decode.⁹⁶

When a received signal is of low level due to significant path loss, reflections, or other interference, the receiver might mistake one message for another. The Bit Error Rate (BER) is the average percentage of bits that are changed during a given period of communication for a digitally modulated system like most of the ones currently used in robot communications. A system's reliability is dependent upon having a low BER. Most systems detect errors if the BER is low enough, and then either fix the errors at the receiver via forward error correction (FEC) embedded in the received signal, or the system requests retransmission of the erroneous data. BER can be minimized by ensuring a high SNR.

The following three figures show the effects of path loss for a 100 mW, 2.4 GHz signal. Figure 30 is a plot of free space path gain vs. distance, while Figure 31 plots excess link margin (ELM) vs. distance, and Figure 32 shows Shannon capacity vs. distance. It can be seen that for distances where the link margin approaches zero dB in Figure 31, the Shannon capacity of the link plotted in Figure 32 also decreases below the capacity level for the corresponding bandwidth of the transmitted signal. An interesting feature of the Shannon theorem is that as the bandwidth of the signal increases, the maximum transmission distance for an acceptable BER decreases. A 20 MHz signal (purple line) has the greatest capacity yet the shortest successful transmission range while maintaining its anticipated capacity.

⁹⁶ "Signal to Noise Ratio Explained," <http://www2.rad.com/networks/2006/db/snr.htm> (Accessed March 4, 2008).

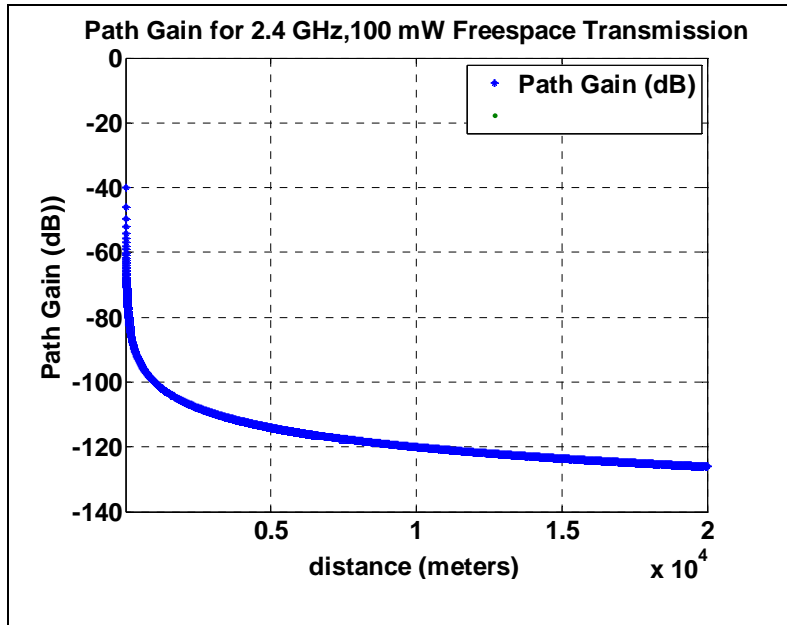


Figure 30. Path Gain vs. Distance

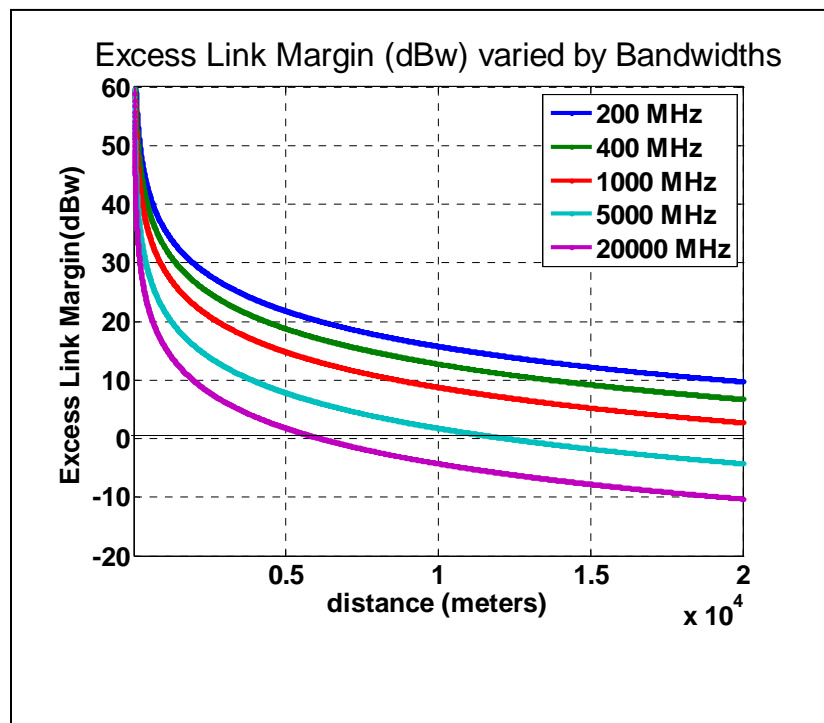


Figure 31. Excess Link Margin vs. Distance

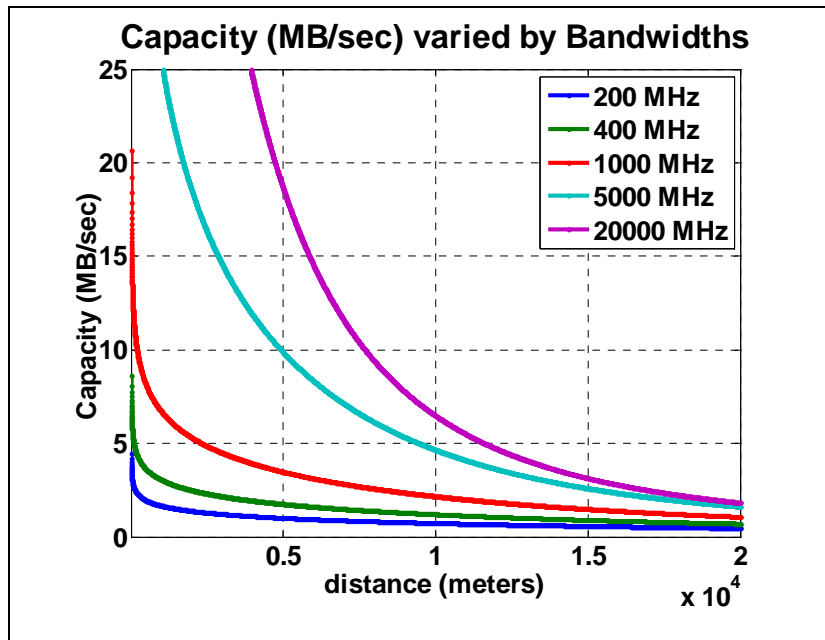


Figure 32. Shannon Capacity vs. Distance

Figure 33 (a-d) reinforces the link amongst all related components – frequency, bandwidth, path loss/link margin, Shannon capacity, and range. These four plots show the excess link margin and Shannon capacity as a function of distance under free space propagation conditions for links having 100 kHz bandwidth and 1 MHz bandwidth. Plots are shown for several different carrier frequencies, noted in the legend. In free space, as distance increases, path loss increases and link margin decreases. If the same signal is sent over a larger bandwidth channel, the capacity of the channel increases; however, the operating range decreases significantly.

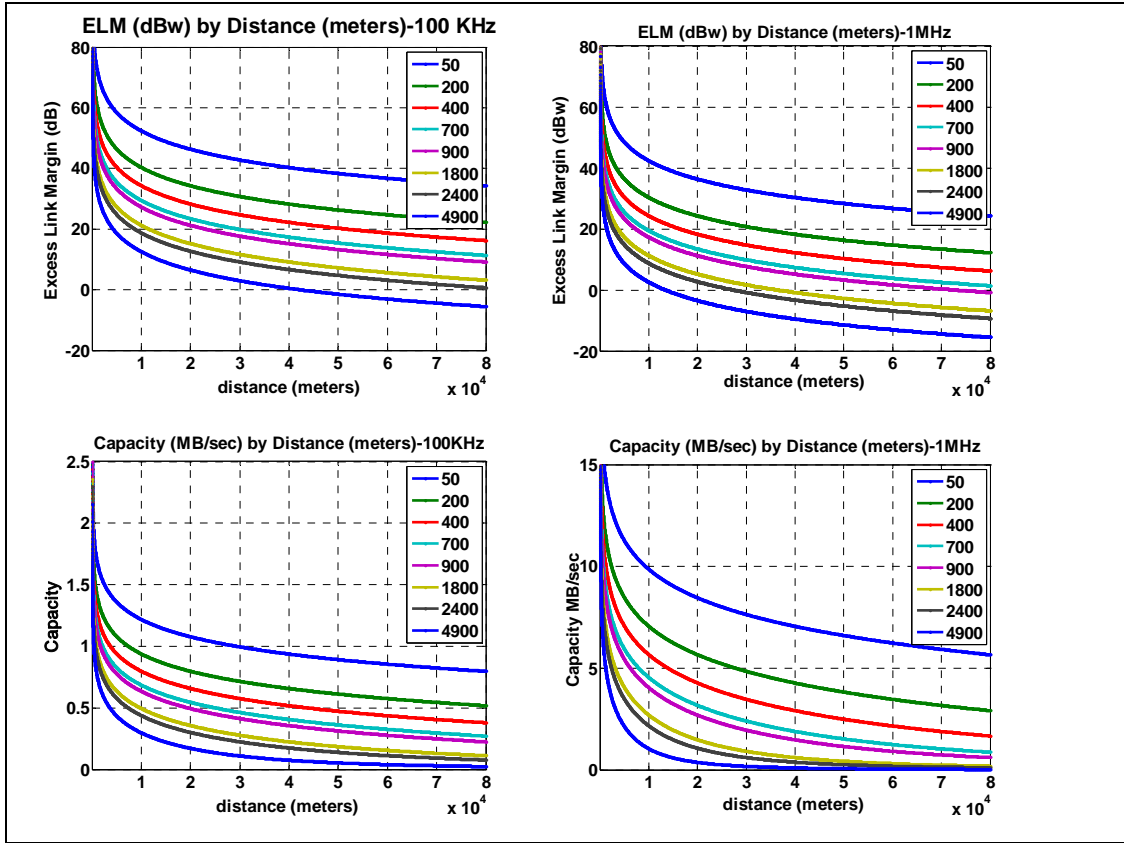


Figure 33. (a-d) – ELM and Shannon Capacity for 100 KHz, 1 MHz BW 33(a) to 33(d): beginning top left and moving clockwise

While trying to minimize BER, engineers continuously strive to improve results through:

- Coding techniques, which determine how bits are represented by messages. Not only do symbol coding techniques reduce the occurrence of errors, but often extra bits are transmitted so that the receiver can fix any errors that may occur. This is called forward error correction (FEC).
- Modulation methods, which determine how messages are represented by signals.
- High SNR, which determines the ability to distinguish a signal in comparison to noise.

Digital communication affords engineers the ability to transmit and receive signals in noisy environments with relatively low error rates, and as a result is rapidly replacing analog communication in many fields. The signal-to-noise ratio (SNR) also impacts the "quality" of digital communication by determining the length of time it takes to transmit the information. In real-time applications such as robotics, there is a limit to the time for retransmitting video before the information is no longer relevant. However, if the robot camera had the capability to take a higher resolution still photograph of an important area such as a crack in a supporting member of a structure, the photograph might be sent at a lower data rate, similar to the manner in which NASA receives images from deep space probes. In addition, a minimum video rate of around 10 frames per second may be more desirable for real time video, as it will reduce the necessary bandwidth while remaining acceptable to the operator.⁹⁷

One reason that robot manufacturers have utilized ISM bands is that the video returned by the robot requires substantially more bandwidth than is available in public safety licensed bands. Determining the minimum acceptable bandwidth necessary to deliver "useable" video for public safety applications is an area currently under investigation. The National Telecommunications and Information Administration (NTIA) is assisting in determining requirements for video for public safety, and DHS Office of Interoperability and Compatibility has recently contracted with a private company to conduct further studies to assess acceptable video.⁹⁸ NIST is also assisting in developing a uniform set of test methods for the US&R robot standards' effort to determine acceptable video for robots. Although encryption may also decrease capacity, the extent varies greatly and depends upon the type of encryption used. While important, encryption is beyond the scope of this discussion.

In addition to the bandwidth requirements for video transmission, the number of video images is an important consideration. In tests conducted in the study by Shiroma

⁹⁷ Margaret Pinson, Stephen Wolf, and Robert B. Stafford, "Video Performance Requirements for Tactical Video Applications" (presentation at IEEE Conference on Technologies for Homeland Security, 2007), 87.

⁹⁸ Noblis Awarded \$1.8 Million Cooperative Agreement for Security, Video-Quality Research, http://www.noblis.org/NewsReleases_4192.asp (Accessed March 9, 2008).

and others, a minimum of two visual perspectives has been found useful for navigation.⁹⁹ Thermal imaging cameras are becoming smaller in size and provide many benefits for both fire and law enforcement applications. LIDAR/LADAR imagers have been added to research robots for creating detailed representations of spaces. Robots are also being applied to the task of creating maps of areas they enter – one technique being Simultaneous Localization and Mapping (SLAM). Industrial, scientific, and medical (ISM) unlicensed spectrum has sufficient bandwidth to fulfill these requirements, although not all devices can or should be used at the same time due to the bandwidth considerations previously mentioned.

Since ISM bands are general-use frequency bands that do not require the user to possess a license, robot manufacturers are afforded a much more cost-effective means of designing hardware to be used in many locations across the country that eliminates the need to change or reprogram equipment, or obtain licenses. While it is true that robot manufacturers are beginning to offer adaptable communication capabilities, response agencies currently do not possess spectrum that supports broadband video applications – although the 700 MHz spectrum auction offers a potential alternative that will be discussed later in this paper.

3. Protocol and Interference

One of the more common protocols for the highly utilized 2.4 GHz band is the 802.11b protocol. Many wireless local area networks (WLANs) utilize this scheme with their access points so that notebook computers can access the internet wirelessly. 802.11b subdivides the frequency spectrum into 11 channels, with three 20 MHz wide non-overlapping channels available for use collectively at any one time. Figure 34 depicts the architecture of this protocol.

⁹⁹ Naoji Shiroma, Noritaka Sato, Yu-huan Chiu, Fumitoshi Matsuno, “Study on the Effective Camera Images for Mobile Robot Teleoperation” (presentation at *13th IEEE International Workshop on Robot and Human Interactive Communication*, 20-22 Sept. 2004), 112.

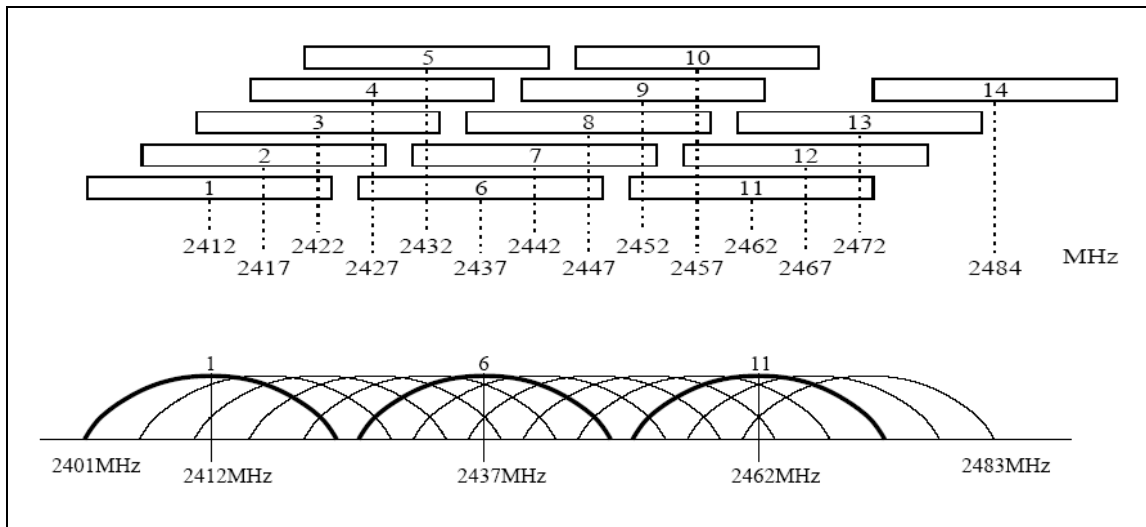


Figure 34. 802.11b 2.4 GHz Channels¹⁰⁰

Stationary wireless networks have multiple access points with a central controller to coordinate the network, and assign non-overlapping channels to neighboring access points so that they communicate without interfering with each other. Individual terminals such as laptop computers identify with a particular access point. Multiple terminals that are linked to one access point are assigned time slots in which they can communicate in the shared frequency band. As more end users connect there are fewer time periods available to communicate. The requirement for a central controller to act as a ‘traffic cop’ in coordinating multiple users in order to avoid interference makes it difficult for first responders to use 802.11b effectively for multiple robots and other wireless devices at an incident. Responders that arrive in an ad-hoc manner during the initial few minutes of a response do not normally have the time to coordinate frequency channels with other responding agencies at the outset. Pre-determining channels can be difficult, with three non-overlapping channels serving as the practical limit as shown above. Each control unit and robot act in a sense as a separate access point, without a provision for coordinating its transmission amongst other controllers, potentially resulting in interference. Upon arrival, responders may also find some of the channels’ capacity already in use by nearby

¹⁰⁰ Figure 34 from Paul Fuxjäger, Danilo Valerio, and Fabio Ricciato, “The Myth of Non-Overlapping Channels: Interference Measurements in IEEE 802.11” (Fourth Annual Conference on Wireless on Demand Network Systems and Services, WONS 2007, Obergurgl Tyrol, Austria, January 2007), Slide 5. <http://www.dps.uibk.ac.at/wons/program/WONS2007-fuxjaeger.pdf> (Accessed March 9, 2008).

businesses or residences operating in the ISM band. Even without the channel being in use, there is still a limit to the number of devices – robots or otherwise – that may access this spectrum without creating interference in the same area.¹⁰¹ Exercises conducted by NIST in August 2006 at the Montgomery County Fire Training Center confirmed that interference can occur when a variety of robots are operated without being coordinated in close proximity to each other using frequencies in the same ISM band, as might be experienced at actual emergency incident. The interference problems experienced will be examined in greater detail as one of the case studies in Chapter IV. For now, the categories of interference problems will be outlined.

a. *External Interference Sources*

802.11b technology has grown enormously as seen by the significant numbers of wireless local area network (WiFi) hotspots, cordless cell phones, and other wireless devices operating in a particular geographic area. Witness the large number of WiFi hotspots by accessing www.jiwire.com or www.wi-fihotspotlist.com as an example. A more definitive survey of Chicago and NYC was made looking at spectrum utilization over a short period of time that showed significant usage in ISM 900 MHz and 2.4 GHz frequency bands.¹⁰² The net effect is that this spectrum is congested and unreliable for critical public safety applications.

b. *Conflicition: Near Far Problem*

In a sense, each operator control unit (OCU) and robot have radios that act as a wireless access points. As response agencies arrive in an ad-hoc fashion and place their equipment into operation, the potential for interference increases. A robot operator may be geographically separated from another operator and other devices in the

¹⁰¹ Paul Fuxjäger, Danilo Valerio, and Fabio Ricciato, “The Myth of Non-Overlapping Channels: Interference Measurements in IEEE 802.11” (Fourth Annual Conference on Wireless on Demand Network Systems and Services, WONS 2007, Obergurgl Tyrol, Austria, January 2007), Slide 1.

¹⁰² Mark A. McHenry, Peter A. Tenhula, Dan McCloskey, “Chicago Spectrum Occupancy Measurements & Analysis and a Long-term Studies Proposal,” *Proceedings of the First international Workshop on Technology and Policy for Accessing Spectrum* (Boston, MA, August 02 - 05, 2006). TAPAS '06, vol. 222. ACM, New York, NY, 1, <http://doi.acm.org/10.1145/1234388.1234389> (Accessed March 4, 2008).

beginning the operation. However, as a robot moves closer to the target destination, its radio may receive the signal of another device in proximity to it. 802.11b utilizes 11 channels, but only channels 1, 6, and 11 do not overlap. Even channels 1 and 6, or 6 and 11, can cause interference with each other according to findings of the following study.

It has become a widely accepted assumption that multiple IEEE 802.11b/g transmissions in physical proximity can coexist without interfering each other. This is claimed to be the case when using separate channels with a minimum distance of 25 MHz, e.g. channel 1 and 6, which are often referred to as non-overlapping... in practice, crosschannel interference can be present also between non-overlapping channels if the interfering transmitter is in the proximity of the receiver. This phenomenon is known as the “near-far effect” in wireless communications. On IEEE 802.11b/g this has two main effects: frame corruption due to increased interference noise and channel blocking due to spurious carrier detection. The problem can be particularly serious when using IEEE 802.11 technology to build multi-hop mesh networks.¹⁰³

A recent study by Intel researchers examined the feasibility of co-locating multiple radios within the same device – such as a cellular phone that uses Bluetooth to connect to a headset. The authors detail two coexistence interference scenarios – proximity and collocation. Proximity applies to radios not on the same physical device, with each device’s antennas radiating energy that causes interference. Collocation infers multiple radios that operate on the same device. This offers the potential of mutual interference from radiation between antennas on the same device, along with conduction. Collocation interference is potentially more severe and may be problematic for trying to create a wireless “personal area network” (PAN) for the robot. A physical connection may be necessary to link a chemical sensor that is added to a robot to relay data through the main communications link with the controller, although a standard interface will be required for creating this functionality amongst many different robots.

¹⁰³ Fuxjäger, “The Myth of Non-Overlapping Channels,” 1.

The second interference factor - proximity - will most likely pose the biggest challenge because no common communication channels exist between devices employing different protocols – e.g., 802.11b and Bluetooth.¹⁰⁴ The authors of the aforementioned article note that

...almost all of today's IEEE standards related to coexistence are media dependent, and are targeted at mitigating co-channel interference that comes from other in-band devices. There is relatively lack of unified approach to measure, detect, and avoid coexistence interference from out-of-band (e.g. receiver blocking, transmitter noise, and intermodulation interference). For example, if there are 6 radios on a platform, we need to consider $2^6 - 1 = 63$ interference scenarios (that has more than one radio). Hence, increasingly we need to standardize a media-independent coexistence service layer, integrating various coexistence techniques and providing a unified and scalable multi-radio coexistence support.¹⁰⁵ (See Appendix C for further information).

They conclude by offering that coexistence interference among these radios is becoming the key limiting factor in both collocated and close proximity environments – as is already being experienced by some agencies due to increased wireless use of devices in the same geographic area, such as laptops, video cameras, thermal imaging cameras, etc.

4. Modulation Techniques

In a comparison of Direct Sequence (DS) Spread Spectrum to Frequency Hopping (FH) Spread Spectrum, 802.11a or g (FH) does better than Spread Spectrum 802.11b (DS) in ad hoc networks according to the author, who states,

Frequency hopping (FH) — interference avoidance — should generally be preferred to direct sequence (DS) spread spectrum — interference averaging...both FH and DS incur considerable overhead in code acquisition and synchronization, and this overhead needs to be amortized to make spread spectrum competitive. Unless new efficient schemes can

¹⁰⁴ Jing Zhu and others. "Multi-Radio Coexistence: Challenges and Opportunities" (*Proceedings of 16th International Conference on Computer Communications and Network*, Honolulu, HI, August 13-16, 2007), 358.

¹⁰⁵ Ibid., 362.

be developed, this trait discourages the use of spread spectrum in ad hoc networks with high levels of mobility or bursty traffic.¹⁰⁶

Figure 35 shows a comparison of different modulation technique performance in relation to the presence of noise. As the signal decreases in relation to noise, the probability of a bit being received as an error and requiring retransmission increases. Simulation of 802.11b at 1 Mbps (without a RAKE receiver) and 802.11a at 6 Mbps is shown. The different curves for 802.11b correspond to different RMS-delay-spreads. For a delay-spread of 7-220 ns, 802.11a gave the same relationship between SNR and bit-error rate, hence this relationship is shown with a single curve.

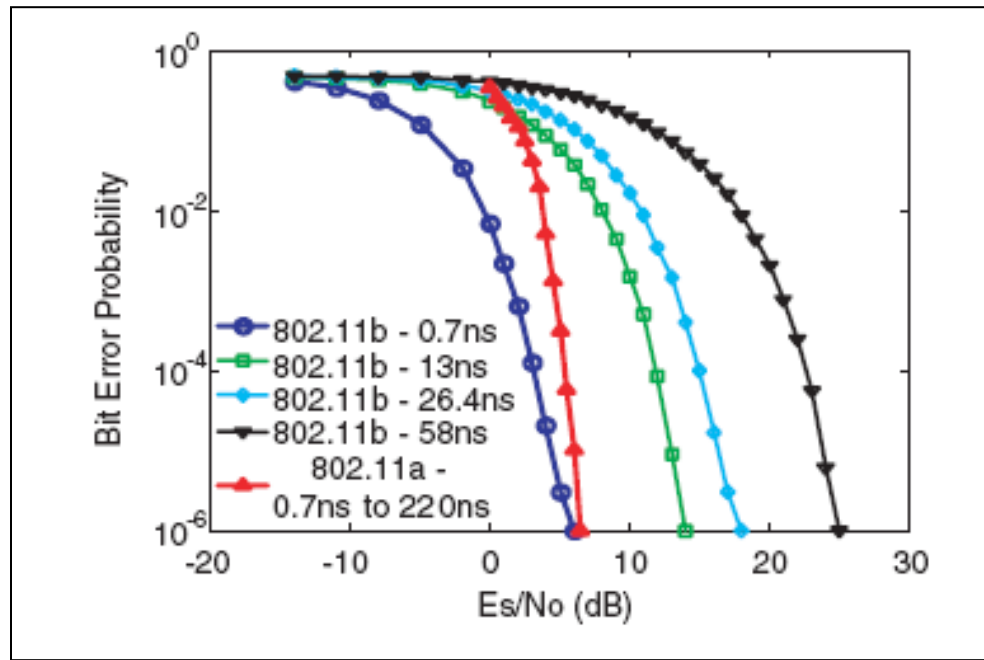


Figure 35. Bit Error Probabilities as a Function of Delay-Spread and SNR ¹⁰⁷

¹⁰⁶ J. G. Andrews, S. Weber and M. Haenggi, "Ad Hoc Networks: To Spread or Not to Spread?" *IEEE Communications Magazine*, 45, no. 12 (December 2007), 90.

¹⁰⁷ Figure 35 from Sridhara, "Realistic Propagation Simulation of Urban Mesh Networks," 3401.

E. EXTENDING THE RANGE OF ROBOT COMMUNICATIONS

One common solution to extend the reach of a wireless signal is to use directional antennas in a wireless system. However, use of directional antennas with robots would prove very difficult, given that a robots need to maintain a two way link, and would consequently need to maintain a directional orientation pointed towards the operator control unit (OCU) at all times. Another approach for extending wireless coverage involves using additional robots and/or repeater bricks to extend the reach in a long tunnel or along a street to maximize the distance between links. The U.S. Navy SPAWAR agency has developed a radio relay package that automatically deploys a repeater brick when it senses a decrease in received signal strength between the OCU and robot. A repeater brick is dropped from a holder that can accommodate six devices. Once the repeater hits the ground it unfurls an antenna mast (approximately 36 inches) and begins to relay the signal.

Across an open space, a signal's path loss curve can be expected to follow a uniform decreasing trend (monotonic) after the Fresnel breakpoint according to the flat earth model. However, in a high multipath environment, signal strength varies significantly and may lead to repeater deployment sooner than is necessary. In addition, spatial, frequency, and temporal fades may contribute to repeater deployment at a less desirable time, and/or in a fade region. An additional consideration is whether the 802.11 ISM band would effectively work in an urban environment. It may suffer similar interference problems as have been encountered previously at the robot test events.

In June 2007, the Defense Advanced Research Projects Agency (DARPA) Information Processing Technology Office (IPTO) issued a Broad Agency Announcement (BAA) for proposals to be submitted on the design of LANdroids – a system of small, inexpensive, autonomous radio relay nodes that the military can drop into an urban area, setting up a wireless mesh network to maintain communications for soldiers. The intent of the system of devices is to adapt to fades and shadows, or nodes being destroyed during combat, in order to maintain a wireless link in non-line-of-sight

(NLOS) conditions throughout the course of the mission.¹⁰⁸ Potential solutions may hold promise for range extension for robots for public safety, as well as for the military.

An important consideration may be whether sufficient bandwidth can be maintained in order to relay a video signal. Figure 36 shows the rate of loss in data rate with each additional hop.

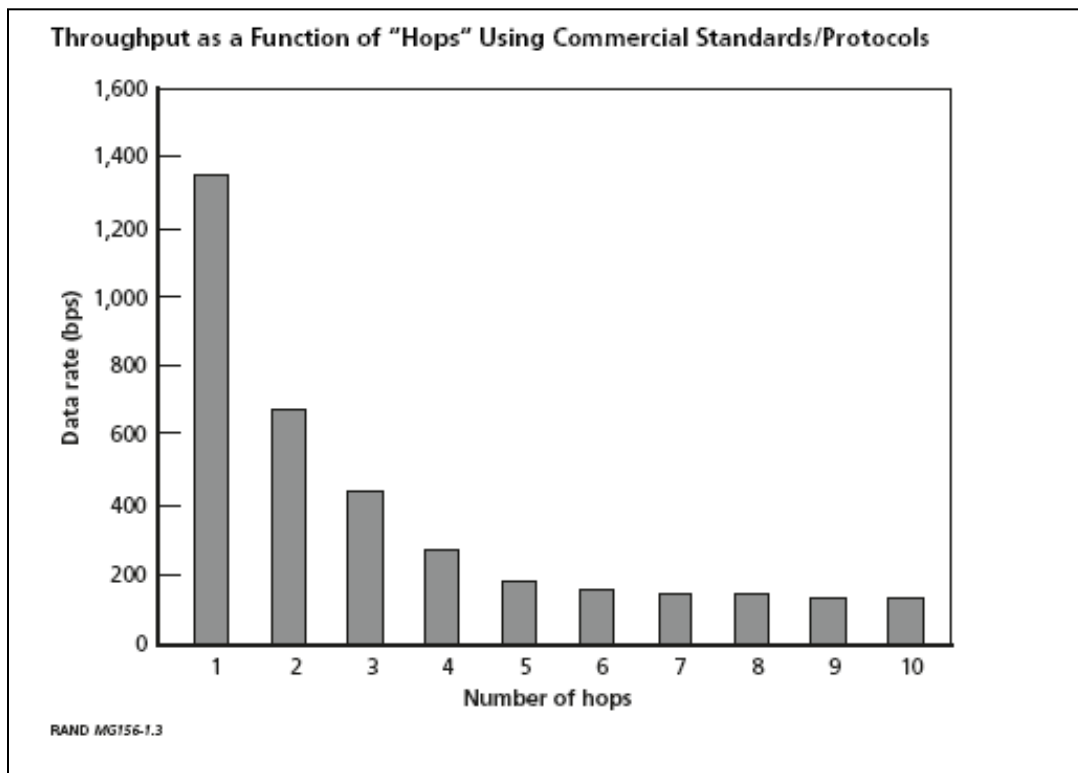


Figure 36. Throughput as a Function of Hops¹⁰⁹

Relaying messages through multihop repeaters is far less efficient than direct connections, but may be the only choice for operating wirelessly given a distant existing situation. Figure 36 shows analysis from Holland and Vaidya (1999) that

¹⁰⁸ BAA 07-46 LANDroids Broad Agency Announcement (BAA) for Information Processing Technology Office (IPTO) Defense Advanced Research Projects Agency (DARPA) (Washington, DC: Defense Advanced Research Projects Agency (DARPA), 2007) http://www.darpa.mil/ipto/solicit/open/BAA-07-46_PIP.pdf (Accessed February 7, 2008).

¹⁰⁹ Figure 36 from Joe, Future Army Bandwidth Needs and Capabilities, 5.

assumes a network of 2 Mbps wireless radio transmitters using the transmission control protocol (TCP). The 2004 Rand study Future Army Bandwidth Needs and Capabilities concluded:

[Holland and Vaidya's] observations show how network capacity diminishes exponentially based on the amount of hopping. Furthermore, these simulation results are in line with Gupta and Kumar's (1999) theoretical findings regarding network scalability with omnidirectional antennas, which suggest a similar decline based on just the numbers of nodes; simply put: the larger the network, the more hopping required and thus the less overall capacity.¹¹⁰

A critical need also exists to link the view from the operator control unit to the incident command post in order to enhance the overall situational awareness at the incident. In a subway, this may entail stretching a cable to the point of operation. If this is attempted on a city street by wirelessly relaying the image, the data rate may drop further. In studies conducted at the Naval Postgraduate School TNT-MIO exercises, a bottleneck has been found to exist at a point where disparate communication technologies meet and hand off data in a transmission link – similar to the point that an OCU would relay a video image to a viewer at a command post.¹¹¹

¹¹⁰ Joe, Future Army Bandwidth Needs and Capabilities.

¹¹¹ Dr. Alex Bordetsky (CENETIX Director, Naval Postgraduate School), in telephone discussion with author, February 2008.

IV. SCENARIOS

In the simulated scenarios that follow, potential situations where robots may prove useful will be examined with the intent to study the radio propagation issues using the models developed in Chapter III. The goal is to link the three areas of consideration – operational, physical, and radio environments – to assess the feasibility of employing a robot for a particular application. The fourth scenario provides an account of field tests conducted at a DHS-sponsored NIST/US&R training event, and is illustrative of the significance of the interference effects that may be encountered.

Power levels will be kept at 1 watt for simplicity in the first three simulated scenarios. As additional power is applied from a transmitter to send a signal to a distant transceiver, the distant device must also raise its power level to return a signal to the initiating device in order to maintain a long-distance two-way link. Typically, increasing transmit power requires increasing battery size in order to maintain the same operating time, which is less than desirable for devices that are intended to be carried by responders to the point of use. The increase in transmission power does not directly translate into a greater operating range, as the relationship is not linear. Finally, increasing operating power also leads to the potential of causing greater interference. Thus, increased operating power will not be considered as a means to increase range for the following scenarios.

The modulated signal bandwidth will be assumed to be 1 MHz, and the control and data links will be on the same channel for simplicity. As was discussed in Chapter III, the operating bandwidth has a significant effect on both capacity and operating range.

The scenarios will take the position that in order to maintain a suitable communication link with a low signal-to-noise ratio (SNR) – in digital communications referred to as the bit error rate (BER) -- a margin (cushion) of approximately 15 dB over the single-frequency link budget may be necessary. While this margin could be improved upon by manufacturers to a small degree, the intent of a large margin is to provide a higher likelihood of maintaining a link in challenging RF environments. By subtracting

15 dB from the link margin calculations, most of the small-scale fading effects of spatial and temporal fast fading will be mitigated. The intent is to show that when the received signal strength falls to within 15 dB of the receiver threshold (which is depicted at the 0 line in the excess link margin (ELM) figures), additional jitter and dropout for the video and possibly the control link may be experienced. In reality, 15 dB may not be enough in high multipath environments and a larger factor would need to be applied in order to maintain a link that might be perceived as more reliable. An operator would employ a robot a shorter distance in this instance before modifying tactics to some degree. The goal for this part of the thesis is to provide a straightforward discussion of the main propagation losses to consider when wirelessly employing a robot in various environments.

A. SCENARIO A: RAIL TANK CAR ACCIDENT WITH HAZARDOUS MATERIALS

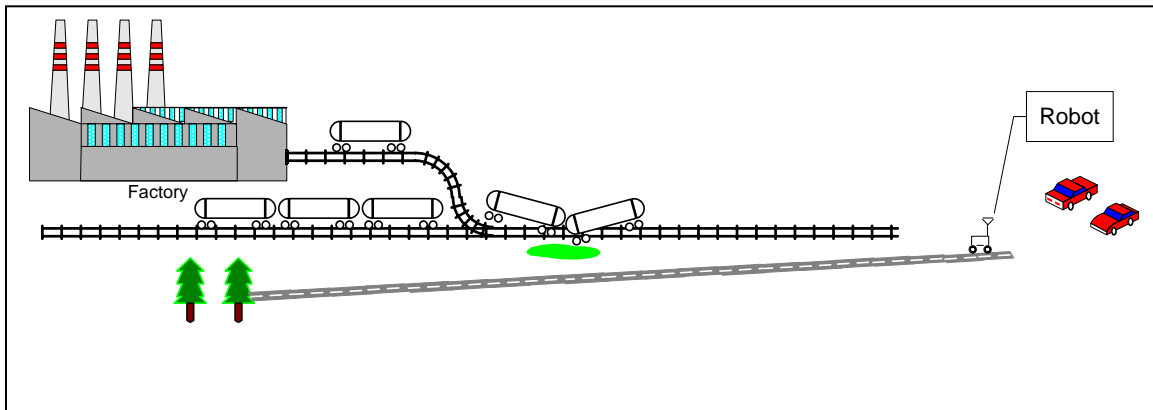


Figure 37. Hazardous Material Tank Car Accident

1. Hazardous Materials Release

On May 2, 2007 at about 4:05 p.m., an industrial switching accident took place when an Acme Rail Line tank car carrying approximately 12,500 gallons of sulfuric acid collided with a tank car containing approximately 24,000 gallons of styrene monomer. As the train entered the facility's track, it collided at approximately 10 mph with the tank car containing styrene, and partially derailed. The two cars remained entangled and a

slow leak began to pool adjacent to the cars; however, it was unclear if the leak came from one tank car or if both tank cars had begun to leak together. Atmospheric conditions led to vapors accumulating in the immediate area without significant dissipation because of low wind speeds that afternoon. The facility managers evacuated their personnel from the area and called 911. The local fire department was dispatched to the incident and first due units began arriving within 15 minutes.

2. Strategic Responder Considerations

The following categories of incident characteristics are of immediate concern to responders:

- Life: Plant personnel, responders, surrounding community
- Environment: Toxic fumes, soil contamination
- Property: Damage to nearby facility from potential explosion

3. Initial Actions

The following actions are crucial to securing a hazardous materials scene:

- Establish Incident Command
- Scene Isolation - 800 meters (0.5 miles) in all directions for responders initially due to the quantity of product and potential for catastrophic release.¹¹²
- Confer with plant and train personnel to obtain Material Safety Data Sheets MSDS and additional information on the contents of all tank cars.

4. Hazard Assessment

The Incident Commander (IC) knows at this point that there is a crash involving a tank car of styrene and a tank car of sulfuric acid, but is unsure whether the leak is coming from one or both tank cars. The IC needs to know if both tanks are leaking and

¹¹² U.S. Department of Transportation, *Emergency Response Guidebook 2004*, Guide 128, (Washington, DC: DOT PHMSA, 2004), 204. <http://hazmat.dot.gov/pubs/erg/g128.pdf> (Accessed March 9, 2008).

could potentially cause a fire and/or a resulting explosion if the products mix. In addition, styrene is normally shipped with a chemical inhibitor added in order to prevent the styrene from reacting with itself to form polystyrene. Depending on the outside ambient temperature and length of time the tank car has been awaiting pickup, the possibility of the inhibitor losing its effectiveness adds to the potential for a runaway polymerization reaction that would result in catastrophic release accompanied by tank shell fragmentation and flying debris.

5. Vulnerability Analysis

Concerning the surrounding community, information gained will help determine the extent of the evacuation necessary. In the interim, the immediate residents surrounding the rail yard within a half mile should be evacuated.

6. Resource Assessment

Adequate resources must be on scene before taking any offensive measures. Hazmat teams are en route. A robot is being transported to the scene for conducting initial reconnaissance.

7. Risk Benefit Analysis

The main life hazard is to any remaining plant personnel, the surrounding community, and the responding firefighters. It would be better to gain information without committing members if possible until the full extent of the hazard is known and sufficient resources have arrived on scene. Information gained will assist with creating an incident action plan involving protective actions, plugging, confinement, containment, off-loading, etc.

8. Tactical Objectives for Employing a Robot

The goal for employing the robot is to obtain close-up video and high resolution still images of the tank cars to determine which tanks are leaking, as well as the size and location of the damage to the tank shell. The location of the leaks is important because

leaks in some locations may form a self-sealing plastic residue, while in other locations cracks may grow if the pressure increases significantly. The information gathered will help the IC make a determination on the type of possible offensive measures to stop the leak. The operator employing the robot must consider which robot platform to use (if there is a choice) and the payload to carry. Video camera, thermal imaging/temperature laser, and chemical sensors should be chosen that are appropriate for the type of release. Ensuring that the wireless link will maintain connectivity is critical because a considerable distance will need to be maintained between operating personnel and the tank car due to the potential for catastrophic release. Wind change and sudden release of the tank contents may necessitate expanding the isolation zone, and these factors need to be considered in the assessment phase of determining whether it is possible to employ a robot wirelessly.

9. Operating Range for Various Frequencies of Interest: Excess Link Margin

Based on the anticipated transmit power, receiver sensitivity, and path loss over flat earth, Figure 38 depicts a link margin assessment of the feasibility of employing a robot 800 meters between a Tx 1.5m and a Rx 0.5 m in height. At 800 m the margin for successful transmission for all responder frequencies is approximately 5 dBW, and at 1000m the link is at just 1 dBW, as shown in Figure 38.

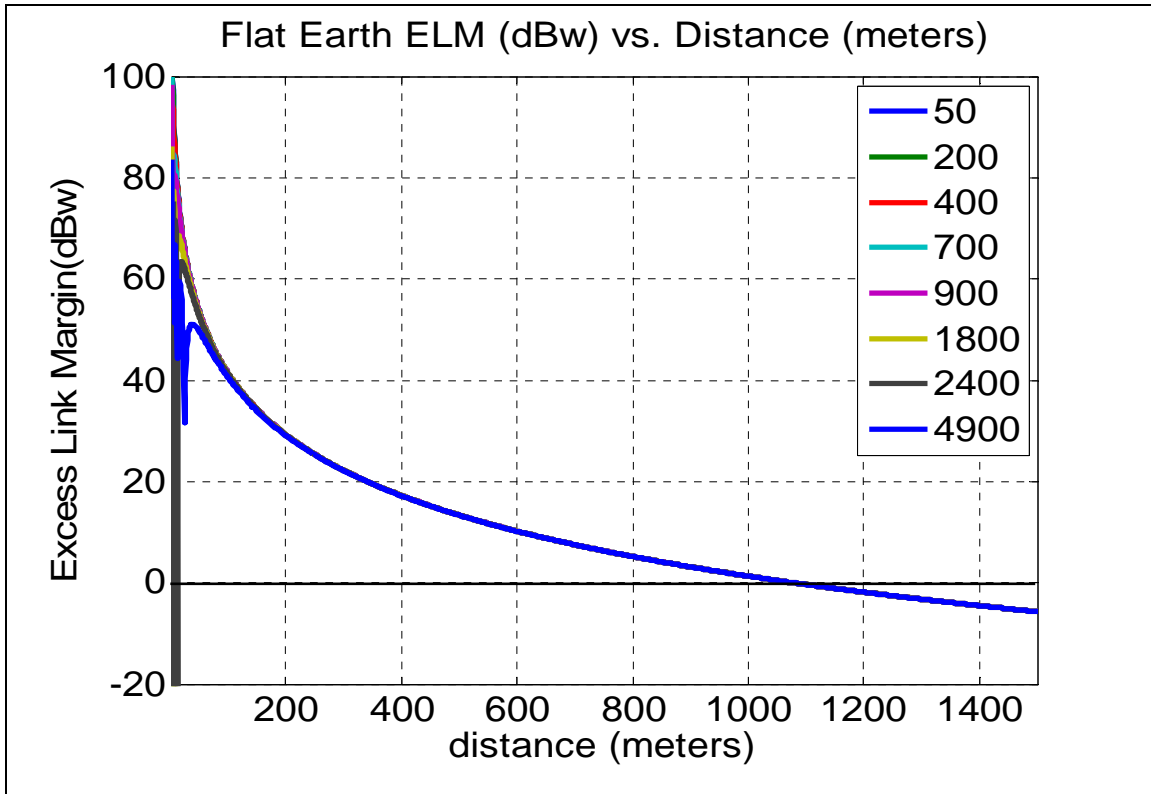


Figure 38. Excess Link Margin for 50 MHz to 4900 MHz Signals

Among the considerations relevant to this assessment, the radio link may be significantly degraded should the robot be required to traverse to the opposite side of the rail car. To improve the range of the link without increasing power, operating the robot from a higher vantage point will significantly improve the received signal strength according to the model. For instance, moving to a height of approximately 10 feet will extend the range to nearly 1400 meters – an important consideration if it becomes necessary to increase the isolation perimeter due to catastrophic release of product while still maintaining video from the robot for monitoring the situation. The presence of trees, buildings, or multiple tracks between the operator and the robot may increase the path loss that might be encountered. As with any intended use of robots, pre-planning the response with consideration of the communications operating range and comparison to anticipated environmental factors is important.

B. SCENARIO B: EXPLOSION IN AN UNDER-RIVER SUBWAY TUNNEL

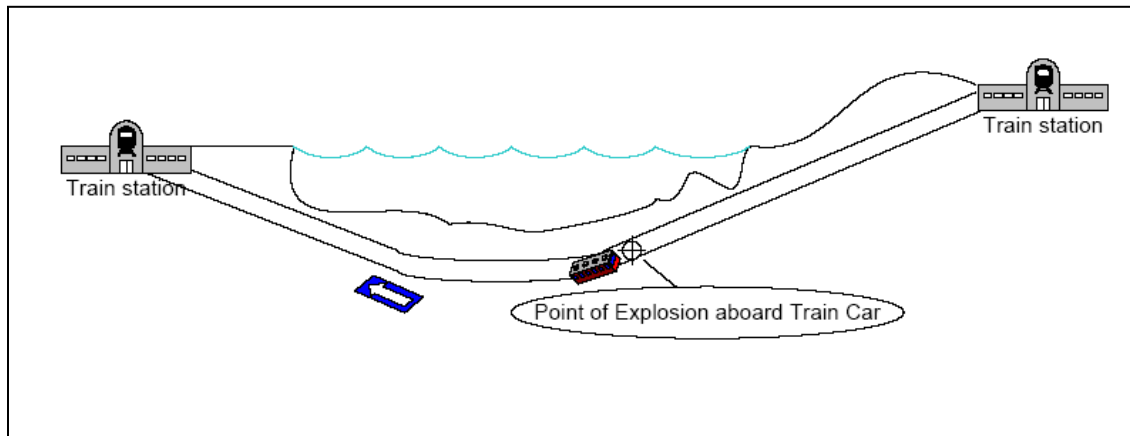


Figure 39. Under River Subway Explosion

A subway train proceeds through a 5,000 foot long under-river tunnel, passing through a 200m straight portion, through a large radius curve for the next 200m, and then along a straight section when it suddenly undergoes a major explosion as it travels the last third of the way from the destination station in the direction of travel. The train comes to a screeching halt, with numerous casualties in the car that contained the explosive device. The conductor begins evacuation procedures as per plan. He deploys an emergency evacuation ladder, and the ambulatory people begin to evacuate along the track-bed towards the closest station, which is in the direction of travel. The station master activates the smoke ejection fans and pushes the smoke away from the evacuating people, towards the long end of the track. Responders are dispatched.

1. Strategic Responder Considerations

The following categories of incident characteristics are of immediate concern to responders:

- Life: Civilians, Responders, surrounding community especially if CBRN contamination is involved.
- Environment: Smoke, possible CBRN contamination
- Property: Structurally unsound tunnel with additional collapse potential.

2. Initial Actions

The following actions are crucial to securing the under-river explosion scene:

- Establish command
- Isolate the scene around the stations at both ends of the tunnel.
- Gather information on number of people evacuating as well as any information concerning the injured civilians.

3. Hazard Assessment

The IC knows that there is an explosion that was potentially a terrorist event, and may include additional CBRN hazards. A potential exists for additional explosives. Numerous casualties – along with ambulatory victims – are evacuating along a track-bed. The IC needs to commit resources to assist in the evacuation effort from the short end of the tunnel. The IC also needs to ensure that the longer smoke-filled end of the tunnel is searched, and will need to obtain additional assets to complete this objective – specifically re-breathers -- to allow responders sufficient air to reach that end through the smoke. The ceiling of the tunnel (on the long end of the stopped train) needs to be inspected for potential collapse.

4. Vulnerability Analysis

Information gained will help determine whether the structurally unstable ceiling poses a potential catastrophic leak hazard.

5. Resource Assessment

Adequate resources must be on scene before taking any offensive measures. Specialized units for shoring are called to the scene along with additional units to assist with evacuation.

6. Risk Benefit Analysis

There are multiple life hazards – non ambulatory victims, ambulatory victims, and responders. It would be better to gain information on the far end of the tunnel without committing members if possible until the full extent of the hazard is known, and sufficient resources have arrived on scene. Information gained will assist with creating an incident action plan involving response at the far end of the tunnel.

7. Tactical Objectives for Employing Robot

Based on these considerations, there exists an opportunity to employ a small robotic device to assist in determining the nature and extent of the emergency in the under-river subway tunnel. The information that responders would be interested in might include video, thermal data, radiation levels, flammable gas readings, oxygen, carbon monoxide levels, and chemical agent presence. Two-way audio would also be very useful for communicating with potential victims. The goals for robot deployment are:

- Searching the smoke-filled end of the tunnel using thermal imaging camera.
- Obtaining video and high resolution still images of the tunnel ceiling and the train.
- Determining the correct robot platform among the alternatives available. It must have the proper payload (camera) and the ability to navigate over gravel and track-bed.
- Ensuring that the wireless link is sufficient to maintain connectivity.
- Assessing for chemical and radiological hazards.
- Assessing for potential unexploded bombs.
- Establishing two-way audio for communicating with any people encountered.

8. Evaluating the Wireless Signal in the Tunnel

Figure 40 shows the expected link margin for each of the responder frequencies of interest using the path loss model discussed in Chapter III, section C.5.d The lowest loss is seen at the 700 MHz and 900 MHz frequencies. The results agree with the generalized trend that was presented in Chapter III for the Massif Tunnel where the frequencies in the middle range tend to afford the lowest path loss at closer distances. The effect of curvature is also similar to that presented in Chapter III where the loss tends to increase as the frequency decreases in the curved section of tunnel.

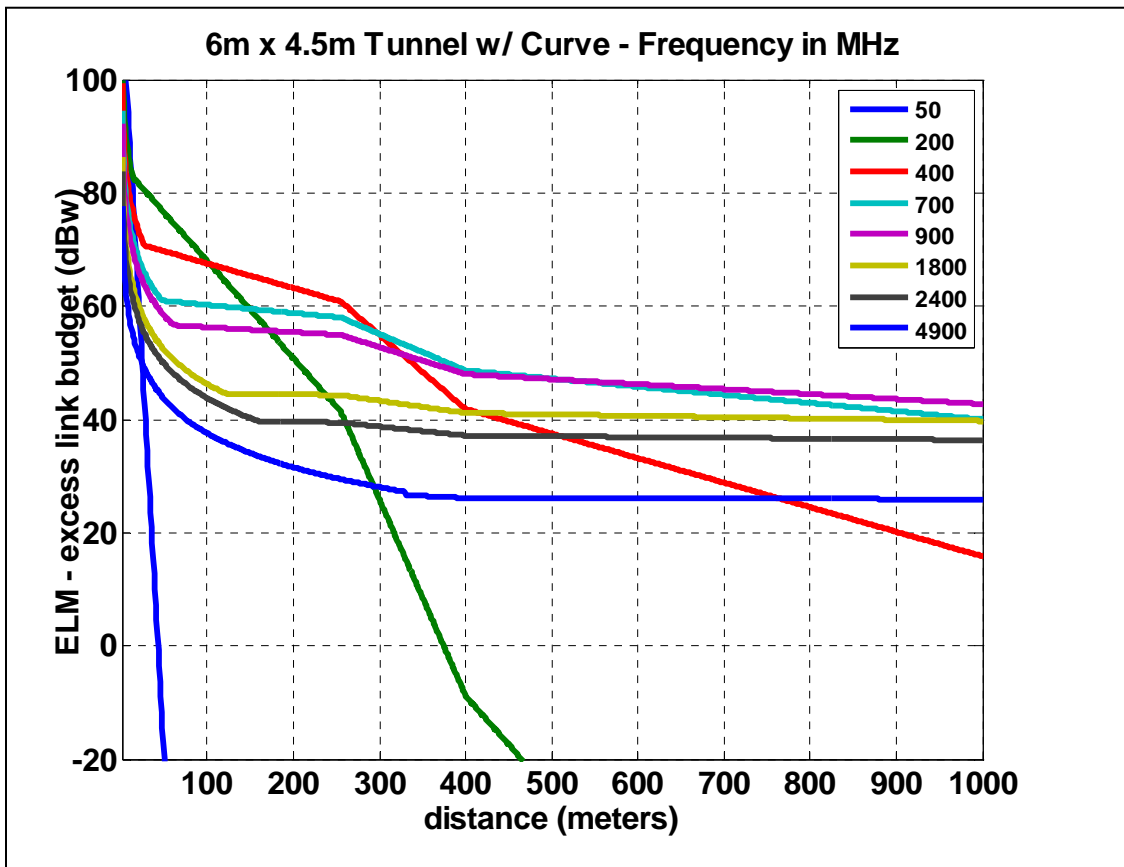


Figure 40. Excess Link Margin for Tunnel with Curvature

9. Considerations for this Scenario

In reality, additional loss may be anticipated in some tunnels due to the additional roughness from the track-bed and conduits, which will tend to absorb energy and increase

path loss. From Figure 40 we see that the 400 MHz signal decreases significantly in the large radius turn. In fact, the rate of loss would increase in turns of a tighter radius of curvature. While the model shows little difference in average signal loss between the frequencies of 700 MHz and 2400 MHz, it is worth noting again that fast fading (significant variation in signal amplitude) is much greater at higher frequencies. Dudley et al. concluded that in both straight and curved tunnels there is little benefit in using increasing frequencies beyond a point where the attenuation loss flattens as frequencies increase (see note 73). This will depend to some degree on the dimensions of tunnel, but for the purpose of subway-sized tunnels, there is little to be gained in operating above approximately 1000 MHz.

C. SCENARIO C: RADIOLOGICAL EXPLOSION IN DOWNTOWN AREA



Note: Figure 41 is from an actual steam explosion incident and is only used for illustrating a potential RDD scenario layout.

Figure 41. Radiological Dispersal Device (RDD) Explosion¹¹³

1. Description of Scenario

At approximately 3:40 on a Thursday afternoon, an explosion occurs in a midtown street with four people severely injured and approximately 20 people suffering

¹¹³“Members Respond to a Steam Pipe Explosion in Manhattan,” (photograph, New York City Fire Department, July 18, 2007). http://nyc.gov/html/fdny/html/units/photo/galleries/2007/071907a/steam_pipe_2.shtml (Accessed February 3, 2008).

minor non-life threatening injuries. A local police officer is among the first on scene, and his radiation pager activates. Upon arrival, firefighters remove the four critical civilians and notice high radiation readings in the immediate vicinity of the most critically injured. The police isolate the area and the firefighters begin to set up a gross decontamination for the less severely injured civilians while additional units are called to the scene.

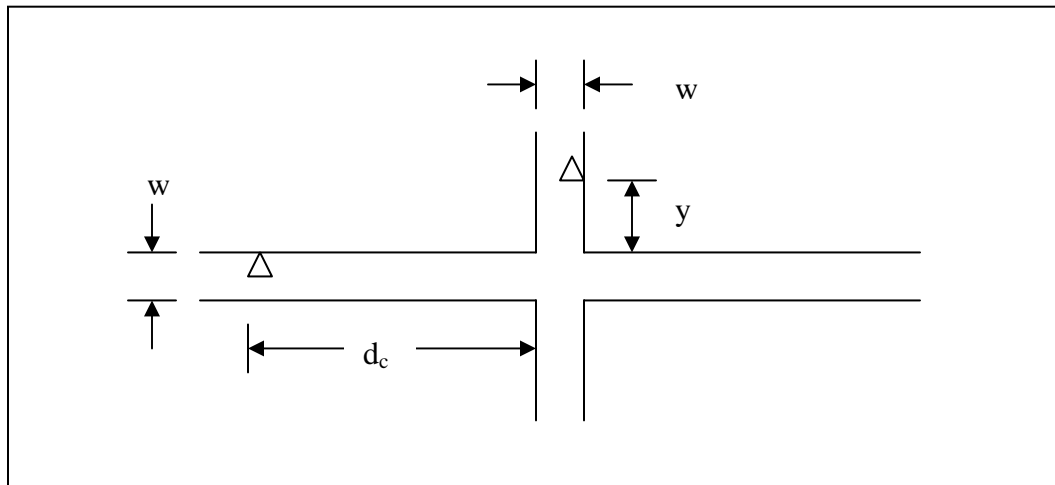


Figure 42. Urban Canyon with Turn (From Appendix A)

2. Strategic Responder Considerations

The following categories of incident characteristics are of immediate concern to responders:

- Life: Civilians, responders, surrounding community
- Environment: radiological contamination
- Property: the surrounding buildings and street

3. Initial Actions

The following actions are crucial to securing the scene at a downtown explosion site:

- Establishing Command
- Isolating the scene and setting up hazard zones. Establishing an initial exclusion zone of 500 m in all directions until adequate detection equipment is available on scene.¹¹⁴
- Ensuring proper respiratory, PPE, and dosimeters are worn by all responders entering area.
- Ensuring assets are available for decontamination of civilians and responders.
- Assessing the extent of contamination.
- Attempting to identify the material with a gamma spectrometer, and reach-back to the Domestic Nuclear Detection Office (DNDO) for confirmation on the device's analysis results.

4. Hazard Assessment

Without any additional information, a conservative initial isolation zone of 500 m should be established according to information provided by Musolino and Harper (see note 114). A perimeter survey should establish an exclusion zone boundary of 10 mSv/hr (1 rem/hr). The designation of this line may be adjusted from 500 m, and will depend upon the type of material and form used in the explosive device, and extent of scatter of radioactive fragments. In this scenario, firefighters using a handheld isotope identifier receive readings for Co⁶⁰. Cobalt in metallic form has a tendency to fracture into large pieces and partially aerosolize.¹¹⁵ After the immediate area has been evacuated, the major life hazard is to the responders. The goal at this point is to map the extent of the highly contaminated area so as to minimize the amount of exposure to responders and other personnel that may be sent in to mitigate the contamination. One possible way may

¹¹⁴ Stephen V. Musolino and Frederick T. Harper, "Emergency Response Guidance for the First 48 Hours after the Outdoor Detonation of an Explosive Radiological Dispersal Device," *Health Physics* 90, no. 4 (April 2006): 381.

¹¹⁵ Ibid., 381 and F.T. Harper, S.V. Musolino, and W. Wentz, "Realistic Radiological Dispersal Device Hazard Boundaries and Ramifications for Early Consequence Management Decisions," *Health Physics* 93, no. 1 (July 2007), 10.

be to utilize a robot(s) to acquire a map of the affected area and overlay contamination points onto an electronic map for viewing at the command post.

5. Vulnerability Analysis

Contamination may be embedded in the building walls across from the device. Highly radioactive chunks may be scattered about the immediate area. Responder exposure should be kept as low as reasonably achievable (ALARA). Falling glass may also present a hazard from above the immediate area as a result of the initial explosion.

6. Resource Assessment

Adequate resources must be provided on scene to decontaminate personnel while an assessment of the extent of contamination is taking place.

7. Risk Benefit Analysis

Since additional resources will be called to an area after a radiological dispersal device (RDD), it would be beneficial to assess the extent of the contamination in the interim. Minimizing responder exposure is critical to both keeping exposures ALARA, and to maximize the efficient use of manpower that will be needed to deal with the decontamination efforts that are taking place concurrently. It is useful to operate from around a corner, using buildings as shielding from localized hot spots, and to add an extra measure of safety from a possible secondary device that may not yet have been discovered.

8. Tactical Objectives of Employing Robot

A priority would be to acquire readings from around the corner of the immediate point of the explosion, and construct an electronic map with the radiation readings overlaid onto the map. Proper payload of radiation sensors and video camera will be needed. In addition, the feasibility of utilizing a wireless link should be assessed.

9. Evaluating the Wireless Signal in Urban Canyon RDD Explosion: Urban Canyon Model with Turn onto Side Street

The formula presented in Appendix A for the urban canyon with a turn onto a side street is utilized for calculating the wireless link margin from the scenario above. Significant path loss is incurred in this scenario by traveling 150m, turning a corner, and proceeding 100m onto a side street. Figure 41 shows that the predicted link margin is not sufficient for this operation.

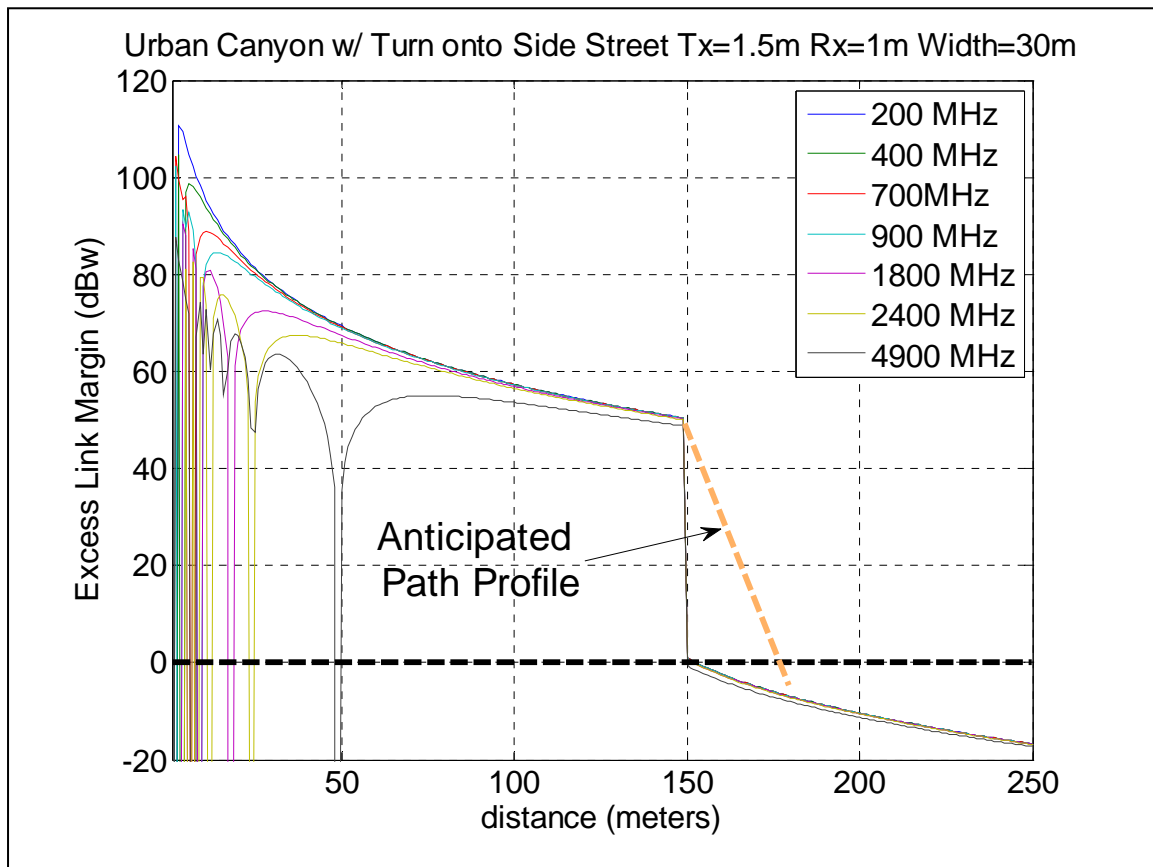


Figure 43. Excess Link Margin

Figure 43 shows that no frequency would permit a robot to even simply turn a corner in an urban canyon under the prescribed conditions. An alternative option would be to transmit from an elevated height. Figure 44 shows the predicted effect if an

operator were placed in a tower ladder basket and raised to 20 m height. The effect that can be seen is that the lower frequencies achieve a better margin, although only a few dB of margin exists to maintain the link.

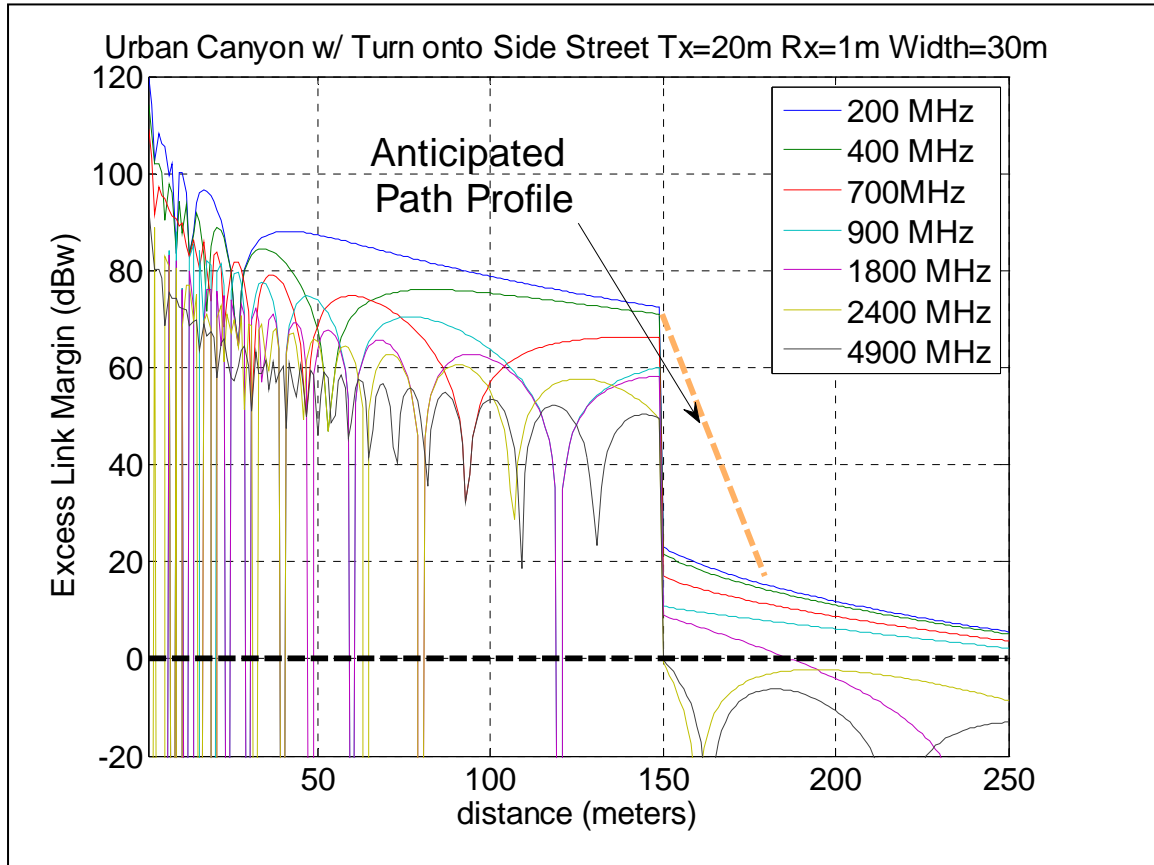


Figure 44. Elevated Transmitter with Turn onto Side Street

A significant degree of improvement might be achieved by mounting a repeater to the underside of a tower ladder which is placed beyond the intersection with the basket extended to a 20 m height over the intersection. Using a digital repeater at this elevation, each leg of the link might look as depicted in Figure 45.

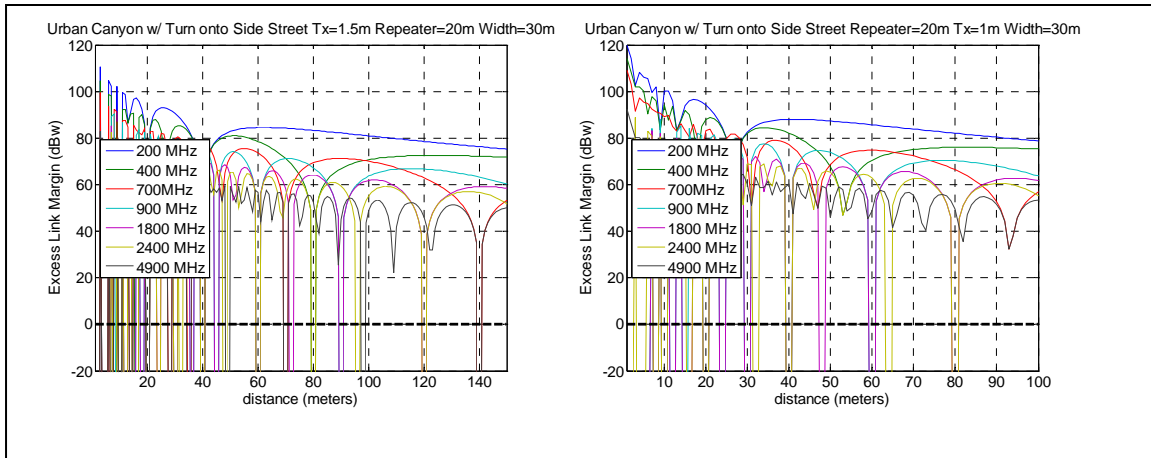


Figure 45. Path Gain Profiles for an Elevated Repeater Tx at 1.5m height (h) to Repeater at 20m (h) to Robot on a Side Street at 1m (h)

10. Considerations

Currently many of the components for achieving the goals of this scenario are in place, although, to this author's knowledge, they have not been combined specifically for this potential application. Much progress has been made over the last few years with Simultaneous Localization and Mapping (SLAM). Robots have been fitted with laser scanners to create two- and three-dimensional maps; at present, two-dimensional maps are significantly easier to achieve with useable results. A novel approach has recently been presented where robots are used to create a map of challenging terrain by utilizing RFID technology for data association.¹¹⁶ GPS will be of little use in such environments for accurate localization and mapping because of the difficulty in receiving a direct satellite signal in high-rise building areas. DNDO has also been working to advance handheld radiation detection and identification technology to rapidly determine the type and location of a radiation source from a distance of 10 to 50 meters, and this approach

¹¹⁶ Alexander Kleiner and Christian Dornhege, "Real-Time Localization and Elevation Mapping within Urban Search and Rescue Scenarios," *Journal of Field Robotics* 24, no. 8-9 (August–September 2007): 723-745.

has been demonstrated on an unmanned ground vehicle.¹¹⁷ Conceivably, both approaches could be married in order to achieve the goals set out in this scenario. Additional methods are worth consideration, but are beyond the scope of this work and are offered for future work.

While radiation hardening of robotic components is somewhat cost prohibitive, the levels of radiation to be expected in a dirty bomb scenario may not necessitate this extent of protection. Long periods of exposure to high levels of radiation may cause the video camera quality to degrade. This can be planned for by having spare cameras to switch out. One might consider that the robot will probably be beyond the point of decontamination if this becomes a consideration.

In terms of the wireless link, a ground-based repeater may be sufficient at the corner intersection for this particular scenario. However, if the extent of the contaminated area turns out to be larger, an elevated repeater affords significantly greater operating margin and is highly desirable for dealing with additional losses that may be hard to predict beforehand in an urban setting.

¹¹⁷ James H. Winso and others, “Geometrically Optimized, Labr3:Ce Scintillation Sensor Array for Enhanced Stand-Off Direction Finding of Gamma Radiation Sources” (Presentation at *2007 Nuclear Science Symposium and Medical Imaging Conference*, Honolulu, HI, October 27 - November 3, 2007). http://www.spawar.navy.mil/robots/pubs/NSS_07.pdf (Accessed March 11, 2008).

D. SCENARIO D: INTERFERENCE EFFECTS

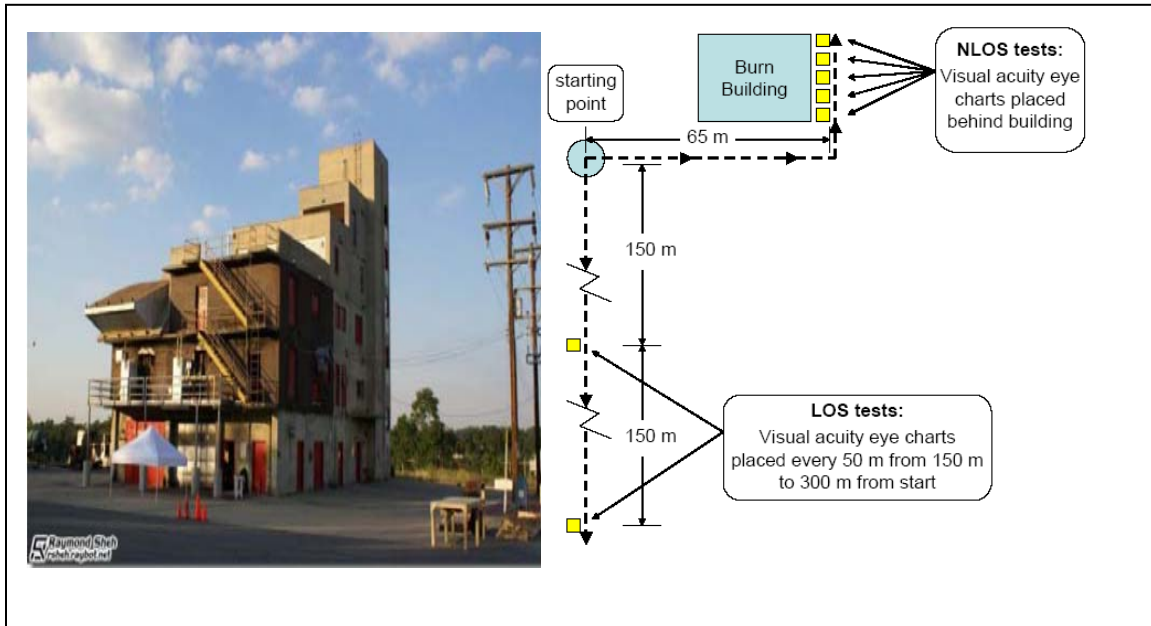


Figure 46. NIST US&R Robot Test Event¹¹⁸

In order to gather data in support of standards development for US&R robots, NIST has been tasked with developing metrics for standardized tests, against which robots might be equally tested and be evaluated. Various robot manufacturers volunteer to participate in these tests by bringing their robots and testing them in simulated US&R scenarios. Test events in Nevada and Texas exposed problems with the communications used to control the robots. During a set of field tests at the Montgomery County Fire Academy in Maryland in August 2006, members of the Electromagnetics Division of NIST developed and carried out a uniform series of spectral analysis tests on each of the robots that participated in the event. Wireless communications were also found to be problematic when robots were operated simultaneously at the site.

In both line-of-sight (LOS) and non-line-of-sight (NLOS) tests, the operator and a NIST engineer were stationed at a fixed location while the robot moved along the course. (see Figure 46). In the LOS test, the robot moved away from the operator down a long

¹¹⁸ Figure 46 from Kate A. Remley et al, "Standards Development for Wireless Communications for Urban Search and Rescue Robots," 68.

flat asphalt lot. Markers that included visual acuity eye charts were placed every 50 m between 150 m and 300 m from the starting point. Control of the robot was monitored continuously, while video data transfer from the robot was checked at each marker.

For the NLOS tests the robot moved about 65m away from the operator in a LOS path, and then turned the corner behind a five-story building which provided the NLOS condition. The following spectrum results were captured during the testing:

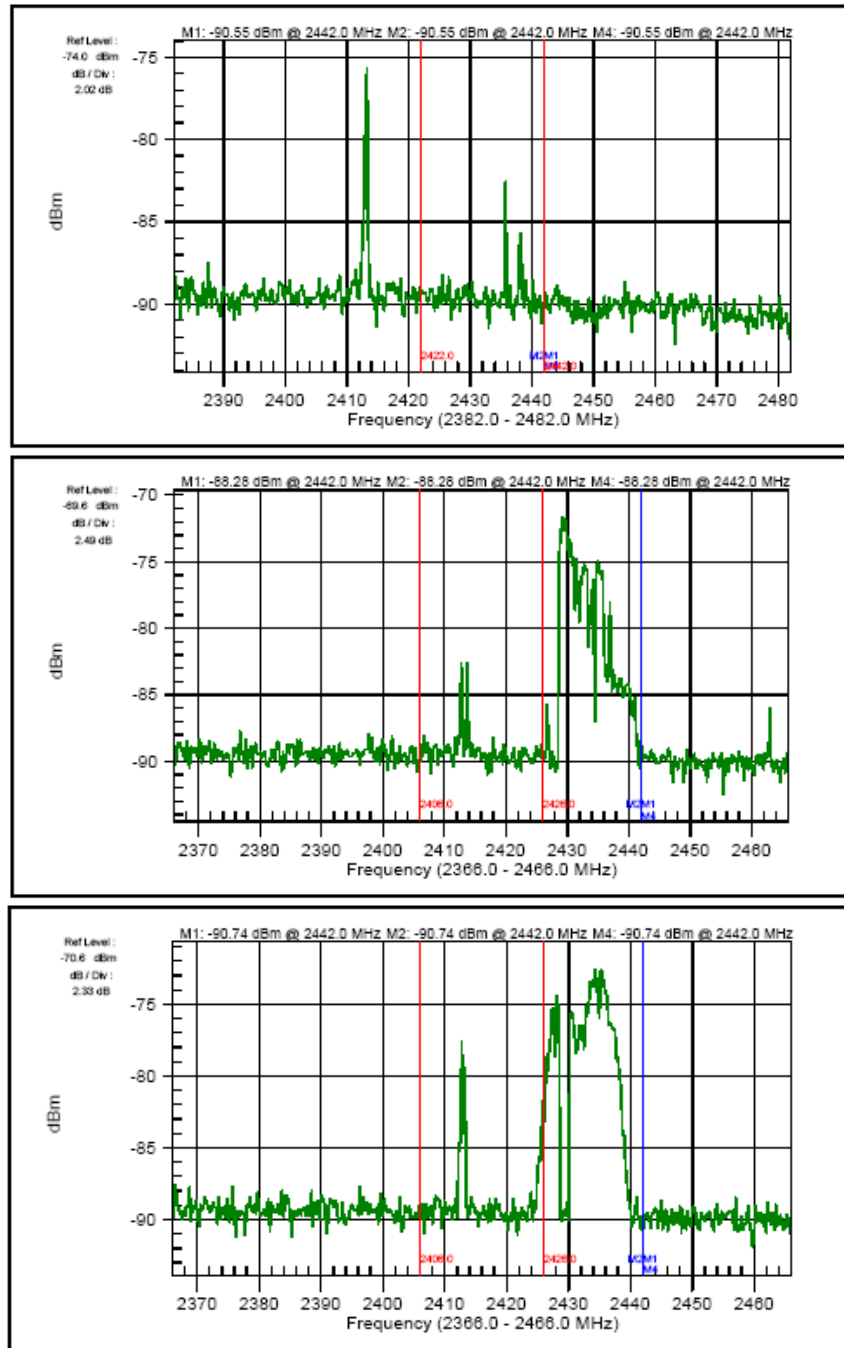


Figure 47. (a-c) - Signal Measurements¹¹⁹

¹¹⁹ Figure 47 (a-c) from Kate A. Remley et al, "Standards Development for Wireless Communications for Urban Search and Rescue Robots," 69.

Figure 47: Example of radio interference to an analog video link transmitting at 2.414 GHz from a nearby robot. In (a), the 2.414 GHz robot is near to the operator and the signal level is high enough for good reception. In (b) and (c), we see that as the robot moves away from the operator, the 2.414 GHz signal level becomes weaker than the neighboring 802.11b signal and eventually the wireless link is lost.

The radio interference environment had a significant effect on the robots' ability to successfully complete the tests. Several of the robots used similar frequency bands and wireless access schemes such as 802.11b. Those with higher power levels often overwhelmed those with lower power levels. An example of this is shown in Figure 47 for a robot that utilized an analog video link centered at 2.414 GHz. As the robot moved away from the operator, its signal became weaker than those from nearby robots. After a certain separation, the link was lost, even though the robot was using an analog modulation scheme that is normally quite robust in weak-signal conditions. Interference was the most significant impediment to radio communication success and had a negative impact on 10 out of the 14 robots that were tested.¹²⁰

The issue of radio interference was cited as an area that “clearly needs to be addressed not only because it degrades the reliability of US&R robot performance in certain situations, but also because it may impact our ability to develop meaningful standards for radio communications.”¹²¹ Through better shielding and filter design, out-of-band interference can be reduced. Limits on operating power set by regulatory agencies including the FCC are necessary to ensure all public safety agencies can operate without suffering harmful interference effects.

¹²⁰ Kate A. Remley et al, “Standards Development for Wireless Communications for Urban Search and Rescue Robots.”

¹²¹ Ibid.

Robot	Video (MHz)	Control (MHz)	Output Power (W)	Success	Failure Due to Interference	Issues with Interference
1	2400	900	0.5	--	NLOS	yes
2	2432	2432	0.2	LOS, NLOS	--	no
3	2437	2437	0.2	LOS, NLOS	--	no
4	2414	2414	?	--	LOS, NLOS	yes
5	2400 (analog)	900	?	--	LOS, NLOS	yes
6	2400	2400	1	LOS, NLOS	--	yes
7	1760	900	1 control, 2, video	LOS, NLOS	--	no
8	1756	900	?	--	LOS, NLOS	yes
9	2400	35	0.1?	--	LOS, NLOS	yes
10	1400	35	0.1?	LOS, NLOS	--	no
11	5200	5200	?	NLOS	--	yes
12	2400	2400	?	LOS, NLOS	LOS, NLOS	yes
13	2400	?	0.1	--	LOS, NLOS	yes
14	2400	2400	?	LOS	NLOS	yes
15	900	75	?	--	--	--

Table 1. Summary of Data Collected by NIST at the August 19-20, 2006 at the Montgomery County Fire Rescue Training Academy ¹²²

The overall impression from this testing is that most of the robots suffered some form of communication related problems – most in the form of signal interference from other robots being operated simultaneously. The data did not conclusively account for which robots, or other equipment, might have been operating at the same time. Theoretically, the degree of interference experienced might even be greater than what was witnessed. The majority of robots that participated in the study operated in the unlicensed Industrial-Scientific-Medical (ISM) bands – 900 MHz, 1.8 GHz, 2.4 GHz – and 5.2 GHz UNII Band.

¹²² Kate A. Remley et al, “Standards Development for Wireless Communications for Urban Search and Rescue Robots,” 71.

THIS PAGE INTENTIONALLY LEFT BLANK

V. ANALYSIS OF RESULTS

A. IMPLICATIONS OF MODELS AND STUDIES UPON FREQUENCY SELECTION

From looking at three common operating environments – flat earth, tunnel, and urban canyon with diffraction around a corner – a general frequency selective trend begins to emerge. In Figure 48, a “sweet spot” for minimizing path loss and maximizing travel distance appears for signal propagation at approximately 500 to 1000 MHz. (Note: the urban canyon graph is not specifically included; however, in this environment the lower frequencies tend to be favored as in free space, especially when operating at modest elevations.) While the diffraction component shown in the third scenario is not included, the lower frequencies suffer less path loss and would also support the conclusion that mid-range frequencies tend to be more desirable. Figure 48 includes the building penetration loss summary data fit curve that was detailed in Chapter III, along with the combined free space and building penetration loss curves for 100m and 500m distances. The building penetration curves also indicate a similar optimal frequency range for urban radio propagation.

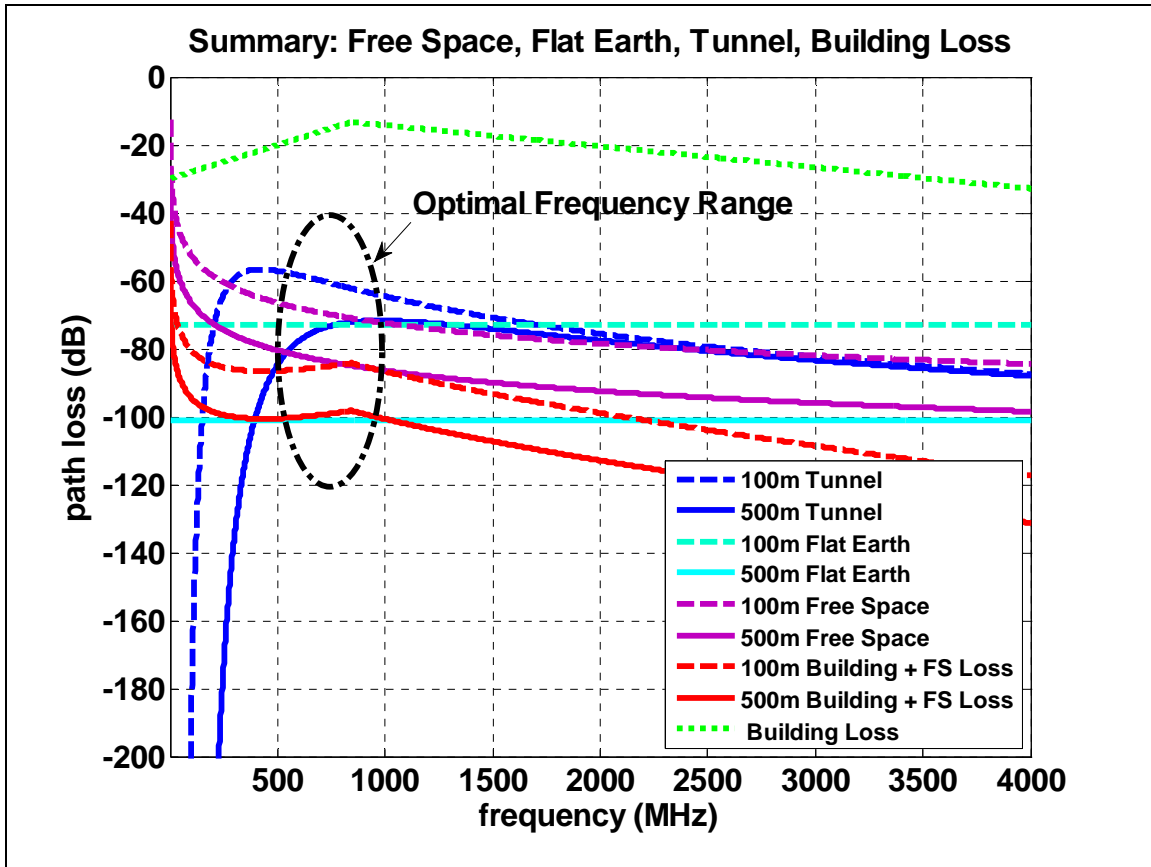


Figure 48. Smooth Rectangular Tunnel: 4.5m x 3.3m, Flat Earth: $h_1=1.5\text{m}$, $h_2=1.0\text{m}$, Freespace

In addition, we saw from the Dudley et al. paper that as frequency increases “there is little to be gained in either a straight or a curved tunnel by increasing the operating frequency beyond the points where the curves flatten” due in part to the increased multipath fading that is experienced.¹²³

The testing conducted by NIST at the Maryland test event demonstrated that a significant level of interference was experienced. Because many commercial devices already operate in the 900MHz and 2.4GHz spectrum, it would be difficult – if not impossible – to find a means for existing equipment to share spectrum with mission critical robot applications without conflicting with each other in these spectrum bands.

¹²³ Dudley, Wireless Propagation in Tunnels, 23.

The most viable option is to look at licensed bands that have sufficient bandwidth to support wireless video and are limited to public safety use, such as 700 MHz and 4.9 GHz. Of these two, the 700 MHz public safety spectrum (10 MHz being designated for public safety use) has significantly better propagation characteristics and might also support a priority access scheme, which is desirable for coordinating multiple public safety agencies at an incident. The 700 MHz band would need to accommodate peer-to-peer access. However, the ability to accommodate peer-to-peer communications is in doubt, along with all of the current plans for public safety utilization of this spectrum as of this writing. The results of the initial auction of the D block attracted a high bid of \$472 million dollars, but needed to hit a reserve price of \$1.3 billion to be activated.¹²⁴ Congressional leaders are planning to hold hearings to assess the next step towards the ultimate goal of constructing a nationwide, next-generation, interoperable broadband network for public safety. A potential opportunity still exists to include peer-to-peer use of public safety devices in the next offering.

Public safety agencies utilizing robots and other wireless broadband devices would also need to adopt a common standard to accommodate an ad-hoc priority access scheme that allows cooperation between users by minimizing the amount of spectrum that they consume, possibly by reducing video frame transmission as described earlier in Chapter III. This would enable more wireless devices to access the same spectrum without sacrificing significant quality from images. In order to most efficiently use available spectrum, priority access should be instituted among public safety devices so that if multiple agencies operate in an area, the most important functions take precedence. Appendix C details an innovative approach to assigning priority access among devices.

¹²⁴ W. David Gardner, "Congressional Hearings Planned on FCC 700-MHz Auction," *InformationWeek*, March 21, 2008.
<http://www.informationweek.com/news/showArticle.jhtml?articleID=206905201> (Accessed March 21, 2008).

Finally, a multi-hop component also needs to be included to enable robotic devices to operate through a repeater without generating harmful interference when no other alternative exists for extending the range of the link.¹²⁵

Another alternative exists in a little known technology: Wireless Ethernet over UHF (WEUHF - pronounced “woof”). This technology was developed by Battelle Inc., and is being applied for robotics use by the West Virginia High Tech Consortium (WVHTC) in conjunction with Nomadio, Inc. A small device provides an interface between two 802.11 / 2.4 GHz devices by converting the signal so that it can be transmitted over a 435 MHz (420-450 MHz) band of spectrum.¹²⁶ The signal is then re-converted by the robot for use upon receipt. The section of spectrum in the 420 MHz to 450 MHz range that is currently occupied by amateur television use may be available for use by federal agencies such as search and rescue teams below a 5-watt power level.¹²⁷ At present, local fire and police departments may still be precluded from using this band under current FCC rules.

Finally, another approach might entail developing an access scheme for wireless devices that “sense” which devices are operating on a particular channel, and dynamically switch frequencies when one is being occupied, similar to a feature in 802.11a. Techniques such as Dynamic Frequency Selection (DFS) and cognitive radio are being developed to accomplish this requirement. Protocols such as 802.11h allow devices to dynamically select frequencies in order to minimize interference with radar and utilize spectrum in a more efficient manner. The National Telecommunications and Information Administration (NTIA) has conducted testing that shows “radar receivers are potentially very vulnerable to interference from communication signals if such systems

¹²⁵ Michael R. Souryal and others, “Real-Time Deployment of Multihop Relays for Range Extension,” (Proceedings of the 5th International Conference on Mobile Systems, Applications and Services) http://www.usenix.org/events/mobisys07/full_papers/p85.pdf (Accessed March 26, 2008).

¹²⁶ Carey Butler (formerly of West Virginia High Technology Consortium Foundation), interviewed by Benjamin Higginbotham about the Killer App Expo, May 2007, http://www.technologyevangelist.com/2007/05/killer_app_expo_care.html. (Accessed March 26, 2008)

¹²⁷ Alex Gizis (Nomadio Corp.), personal communication with author, March 14, 2008.

share spectrum with radars.”¹²⁸ DFS may offer the potential to enable robots to operate in the same area by requiring each control unit and robot to not only minimize their level of interference with outside sources, but also:

- Observe the received power and channels of the receive-to-send / clear-to-send (RTS/CTS) messages from other operator control units that it can observe.
- Act to reduce its’ own perceived interference.¹²⁹

DFS and cognitive radio may be helpful in the future; however, it is still many years from being useful in the field. Efforts to improve the situation should be focused on broadband spectrum in a desirable range that accommodates multiple public safety users in a manner that minimizes potential interference through priority access. Table 2 below summarizes and assesses the options currently available to public safety based on the models presented and the conclusions reached.

¹²⁸ Brent Bedford and Frank Sanders, “Spectrum Sharing and Potential Interference to Radars” (*Proceedings of the International Symposium on Advanced Radio Technologies* (Washington, DC: Dept of Commerce, NTIA 2007), 72. http://www.its.bldrdoc.gov/pub/ntia-rpt/07-445/report_07-445.pdf (Accesses March 20, 2008).

¹²⁹ J. Neel, “Analyzing the Interactions of Cognitive Radios” (dissertation in progress), Chapter 7, 319. <http://mprg.org/people/gametheory/publications.shtml> (Accessed March 11, 2007).

Band	Public Safety Licensed Spectrum Bands						Industrial	Scientific	Medical
	Low	VHF	UHF	700	800	4.9	(ISM) Unlicensed		
Freq Range	30-50	150	450	700	800	4.9	900	1.8	2.4
Units	MHz	MHz	MHz	MHz	MHz	GHz	MHz	GHz	GHz
Interference									
C=controllable	C	C	C	C	C	C	N	N	N
N=uncontrollable									
Path loss/Overall									
Good/Fair/Poor	P	F	F/G	G	G	P	G	G/F	F
Bandwidth									
N: narrow	N	N	N	B	N	B	B	B	B
B: broad									
Priority Access									
S: Suitable									
U: Unsuitable	n/a	n/a	n/a	S	S	S	U	U	U
n/a: not applicable									
Suitability for									
Multi-hop									
Comm.									
Good/Fair/Poor	P	P	P	G	P	G	G	G	G

Table 2. Summary Table of Spectrum Availability for Public Safety

700 MHz – Public Safety Band – 10 MHz with the opportunity to use an additional 10 MHz from the D-Block. Spectrum to be auctioned January 24, 2008 and may become available for use in February 2009. Network build out of base stations will take many years and be managed by the Public Safety Spectrum Trust (PSST).

4.9 GHz – Public Safety use of 4.94 - 4.99 GHz: max bandwidth of 20 MHz/channel.

VI. RECOMMENDATIONS AND CONCLUSION

A. FUTURE RESEARCH OPPORTUNITIES FOR OPERATIONAL, TECHNICAL, AND REGULATORY STANDARDS

This thesis has discussed the wireless use of robots for fire service search-and-rescue applications; fuller incorporation into firefighting operations remains in the future. The decision must take into account logistical concerns such as robot cost, operator training, and maintenance, along with operational considerations such as tactical needs, technical limitations, and reliability. As demonstrated through testing of robot employment for MOUT scenarios by the Swedish military, soldiers benefit from well-defined tactical employment procedures.¹³⁰ Similarly, firefighters need to know in which situations – and for what tactical advantage – robots should be employed. The wireless link is extremely important to the overall perceived reliability and perceived usefulness of a robot. Intrinsic to the wireless link is the interrelationship of the three environments discussed in Chapter III –operational, physical, and radio. Tactics, spectrum, and protocols play a vital role in determining whether a robot can be used as intended, and whether these devices will be useful for responders in the long run.

In order to move the industry forward, a few considerations need to be addressed. First, a new frequency for coordinating multiple broadband wireless devices for public safety is needed. At present, the 700 MHz public safety band (10 MHz of spectrum) is being auctioned as part of a public/private consortium under the auspices of the Public Safety Spectrum Trust (PSST). However, many questions remain as to who will win the next auction, and when the national public safety network would be constructed. Even more critical is the consideration that responders using robots in urban environments need peer-to-peer communication between controller and robot. It is currently unclear if this will be accommodated in planning for the 700 MHz system. Finally, if new spectrum should be acquired for peer-to-peer use of robots, some prioritization scheme – as argued for within the currently preferred option for a 700 MHz cellular-based system – is also

¹³⁰ Lundberg, “Long-Term Study of a Portable Field Robot in Urban Terrain,” 625.

necessary for robots and other devices to sense and prioritize one another, even when operating in an ad hoc mode. Without these wireless requirements, robotics may not achieve the level of reliability to be used in most responses.

In addition to spectrum and protocol concerns, well-defined tactical applications need to be explored in greater detail. By virtue of the number of daily responses, the fire service has a unique opportunity to proactively integrate robots into their response plans during the more routine incidents. This will assist in developing and refining response plans that will be useful when a major event occurs. It should be recognized that a robot is a tool, and as with all tools, responders would need to train with it regularly to remain proficient. In a similar way, a robot will not be appropriate for all responses. However, regular use will help define the bounds of useful applications.

A few current programs offer opportunities for leveraging the process of defining operational uses for robots in the fire service. Currently, NIST, under the auspices of DHS, is assisting the US&R community by developing performance metrics for robots used for US&R. Certainly some of the results of this effort will be applicable to many aspects of the fire service. The approach is a sound one – bringing end users into the test and evaluation process of currently available robotic platforms and making the results available to the general public. The difficulty with developing tactics for the fire service that take into account wireless communications is that each physical operating environment is different. An approach is needed that puts robots into the operating environment and captures lessons learned to be shared among users who can assess for themselves the applicability of the results, and then devise better ways to apply robots in their environment.

An arm of the Navy has put together a pool of robots to assist local responders. SPAWAR – based in San Diego, <http://www.spawar.navy.mil/robots/> – has had a robot loan program over the last four years to offer certain platforms to response agencies to become familiar with the attributes of robots. Law enforcement agencies have predominantly taken advantage of this over the last few years, although a few fire departments have tested robots for hazardous materials response. SPAWAR currently

has plans to expand the program by setting up three to four satellite centers for loaning robots to local agencies. An additional plan includes setting up a web portal to serve as a knowledge base and to capture user experiences.

NIST's Electromagnetics Laboratory in Boulder, Colorado has recently performed detailed spectral analysis of a few typical response environments including multistory residential, office complex, industrial refinery, tunnel, and collapsed buildings (see Remley and others, NIST study referenced in note 139). The data is all publicly available for researchers to use in considering future development of public safety communication systems.

By leveraging the strengths of each agency's respective capabilities, in an iterative managed fashion, a more thorough understanding of tactics and technology might be gained by employing robots in such environments. Currently the Naval Postgraduate School CENETIX lab manages a Tactical Network Topology Maritime Interdiction Operation that brings together military, public safety, government labs, commercial vendors, and students to iteratively improve tactical wireless networking in realistic field testing settings. New equipment is iteratively tested, and lessons learned captured for analysis and improvement during the next test event.

Urban firefighting settings pose their own unique challenges, and lessons learned should be gathered and disseminated for the mutual benefit of improving response operations using robots. The study discussed in Chapter III involving the Swedish MOUT found that the initial expectations for robot use by senior officers did not match end results after a six-month employment strategy. So too robot employment strategy and tactics may not be fully explored by the fire service until working with them in field settings over a period of time. Understanding all facets of the wireless link, and knowing when a wireless system is performing as predicted, will be critical in a thorough comparison of models and test data.

Wireless robotic use shares much common ground with other wireless safety devices that responders seek to deploy in emergency situations. The gap that needs to be addressed is that of fusing the technical, tactical and regulatory issues that link these

multiple efforts. The common goal that all emergency responder technologies should fulfill is to provide improved real-time situational awareness at a disaster scene, thereby increasing safety. Many of the same issues described with respect to wireless robot operation also apply to other responder wireless devices. In the future, one might envision robotic devices even working in tandem with responders to maintain communication links and to investigate hazardous areas in a network-centric response concept.

B. OPPORTUNITY FOR A JOINT ROBOTICS EFFORT

An opportunity exists for developing a managed program to accelerate the feedback development loop for robotics devices. A variety of commercially available robots – such as the ones SPAWAR provides – could be selected for local emergency response agencies to test during drill exercises and at incidents. The proposed program should most likely be overseen by an impartial entity – such as NIST – that would collect basic feedback from response agencies on a periodic basis, and adjust the program in the appropriate manner on an iterative basis. New and more appropriate models could be developed that would serve to improve the predictive capacity for using robots in future environments. Useful guidelines on operating limits for a device based on the anticipated physical environment would contribute towards technology acceptance. Responders may benefit from the following additional components:

- Education – Training guidelines on signal propagation characteristics in different environments can enhance an operator's view of the perceived usefulness of a robot by helping him or her to develop a predictive capacity for future employment. Combining user experience with theory helps to develop the ability to confidently predict the potential success of deploying a robot before actually doing so. The guidelines will depend upon many factors and should be derived from propagation models and pre-incident evaluation of target environments according to the frequency designated for use.

- System feedback – Signal strength indicators could be incorporated for users along with software to interpret the limits of operation based on minimum received signal strength. An acceptable margin – depending upon the variation in received signal strength detected by the controller – might be used to indicate to the user when the limit of operating range is reached.

The focus of this managed effort would be broader than just communications, although modifying communications' payloads and employment methods will certainly be a prime component of the development process. The plan would involve a substantial coordinated effort to ensure that the most appropriate technological solutions are selected to satisfy user requirements and regulatory constraints. Lessons learned from this project would be captured and included into future standards revisions. Additional path loss data that is collected at locations could be included into the public record for development of better predictive models. Unfortunately, much of the existing propagation work has targeted specific frequencies of commercial interest; the information is proprietary, and is therefore unavailable to the larger community of responders and manufacturers.

A decision would also need to be made about developing a separate standard for the fire service, or whether the ASTM US&R robot standard would serve the fire service as well. Standards organizations have a critical stake in the future of broadband devices used for public safety, and need to be incorporated into the process from the start. They play a key role in determining the compatibility of various devices being used in the same vicinity in a complementary manner. Efforts such as ASTM E54.08.01 - Standard for Robots for Urban Search and Rescue - seek to specify through a communications portion of the standard how robotic devices utilized by US&R teams will be verified. Coordination among multiple standards bodies will be necessary to ensure compatibility and interoperability among multiple applications.

Standards alone are not enough to ensure that proper steps are taken for public safety equipment requirements. Currently, the public safety market is very small by comparison with the military market for robots, and even smaller when compared to the

civilian market for broadband wireless devices. Market forces alone will probably not be sufficient to ensure that robots or other devices communicate properly without interfering with each other. Grant money and innovative means need to be used to help ensure compliance.

Ultimately, a responder's view of whether a robot is useful will depend upon the success of his or her experience in employing it during tactical situations. Actual reliability of the system (i.e., without suffering malfunction) will be an important factor, just as Davis concluded in his technology acceptance model. The aforementioned considerations can greatly improve the operator's knowledge base and predictive capacity, thereby affording an increased perception of reliability that also improves the perception of usefulness, the attitude towards using, and behavioral intent to use the device. An enhanced capabilities-based preparedness lies at the heart of the National Preparedness Guideline vision statement. A better understanding of the issues presented in this work may offer additional options for firefighters and other responders to employ devices that will allow them to complete their mission in a safer and more effective manner.

APPENDIX A. FORMULAS

Note: When expressed in decibels (dB), $PG_{dB}=10 \log PG$. $PL = -10 \log(PG)$.

Free Space:¹³¹

$$PG = \left(\frac{\lambda}{4\pi d} \right)^2$$

d= axial distance between transmitter and receiver.

λ = wavelength

Flat Earth:¹³²

$$PG = \left(\frac{\lambda}{4\pi d} \right)^2 \left| 2 \sin \left(2\pi \frac{h_1 h_2}{\lambda d} \right) \right|^2$$

d= axial distance between transmitter and receiver.

λ = wavelength

h_1 = transmitter height

h_2 = receiver height

¹³¹ Henry L. Bertoni, *Radio Propagation for Modern Wireless Systems* (Upper Saddle River, NJ: Prentice Hall Professional Technical Reference, 2000), 94.

¹³² Ibid., 99.

Diffraction:¹³³

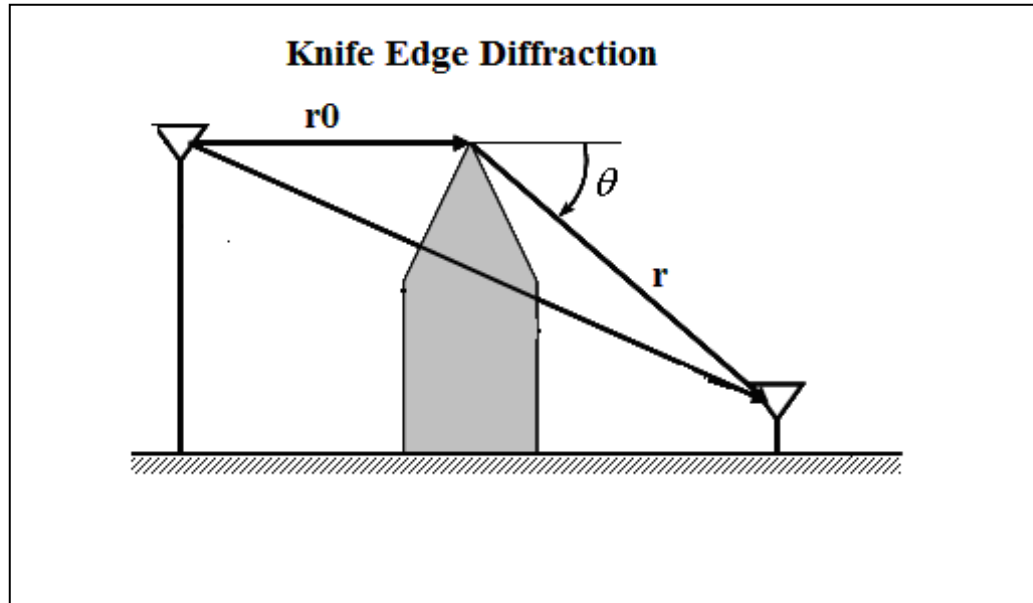


Figure 49. Knife Edge Diffraction ¹³⁴

$$D(\theta) = \frac{-1}{\sqrt{2\pi k}} \left[\frac{1}{\theta} + \frac{1}{2\pi - \theta} \right]$$

$$PG = \frac{P_R}{P_T} = \left(\frac{\lambda}{4\pi} \right)^2 \frac{|D(\theta)|^2}{r_0 r (r_0 + r)}$$

$$\theta = \text{radians}$$

$$k = 6\pi \text{ m}^{-1}$$

¹³³ Bertoni, *EL 675 UHF Propagation for Modern Wireless Systems*, Chapter 9, Slide 10.

¹³⁴ Figure 49 adapted from Ibid.

Tunnel: ¹³⁵

Straight Tunnels

$$L(d) = L_{FB} + \alpha(d - d_{FB})$$

$$L_{FB} = 20 \log \frac{4\pi d_{FB}}{\lambda}$$

$$d_{FB} = \min\left(\frac{a^2}{\lambda}, \frac{b^2}{\lambda}\right)$$

$$\alpha = \alpha_{Tunnel} + \alpha_{Roughness} + \alpha_{Tilt}$$

$$\alpha_{Tunnel} = 4.343\lambda^2 \left(\frac{1}{a^3} \frac{1}{\sqrt{\epsilon_R - 1}} + \frac{1}{b^3} \frac{\epsilon_R}{\sqrt{\epsilon_R - 1}} \right)$$

$$\alpha_{Roughness} = 4.343 * \pi^2 h^2 \lambda \left(\frac{1}{a^4} + \frac{1}{b^4} \right)$$

$$\alpha_{Tilt} = \frac{4.343 * \pi^2 \theta^2}{\lambda}$$

$\lambda = \text{wavelength}(m)$

$a = \text{width}(m)$

$b = \text{height}(m)$

$\epsilon_R = \text{relative_permittivity_walls}$

¹³⁵ Rak, "UHF Propagation in Caves and Subterranean Galleries," 1136-1138.

Formulas for Tunnel Propagation Including a Curved Section¹³⁶

Consider a tunnel of rectangular cross section having width w and height h , and that the relative dielectric constant of the surrounding walls is ϵ_w . Assume vertical polarization of the electric field.

For transmitter and receiver in a straight section of the tunnel, the path gain between isotropic antennas separated by a distance d is given by

$$PG \equiv \frac{P_{Rec}}{P_{Tran}} = \begin{cases} \left(\frac{\lambda}{4\pi d} \right)^2 & \text{for } d < x_F \\ \left(\frac{\lambda}{4\pi x_F} \right)^2 e^{-\alpha(d-x_F)} & \text{for } d \geq x_F \end{cases} \quad (1)$$

Here x_F is the larger of w^2/λ and h^2/λ and

$$\alpha = \frac{\lambda^2}{w^3 \sqrt{\epsilon_w - 1}} + \frac{\lambda^2 \epsilon_w}{h^3 \sqrt{\epsilon_w - 1}} \quad (2)$$

When the path gain is expressed in dB, the formulas in (1) take the form

$$PG_{dB} = \begin{cases} 10 \log \left(\frac{\lambda}{4\pi d} \right)^2 & \text{for } d < x_F \\ 10 \log \left(\frac{\lambda}{4\pi x_F} \right)^2 + \alpha_{dB}(d - x_F) & \text{for } d \geq x_F \end{cases} \quad (3)$$

In this formulation, the attenuation constant is given by

$$\alpha_{dB} = 4.34 \left\{ \frac{\lambda^2}{w^3 \sqrt{\epsilon_w - 1}} + \frac{\lambda^2 \epsilon_w}{h^3 \sqrt{\epsilon_w - 1}} \right\} \quad (4)$$

If the tunnel has a curved section, we first account for the distance into the tunnel such that line of sight (LOS) conditions exist. This is shown in the drawing for a tunnel having a radius of curvature R_c as measured at the center of the tunnel. For this purpose, LOS exists until the extension of the center-line of the straight section touches the curved tunnel wall. For R_c large compared to w , the LOS distance into the tunnel is given by

¹³⁶ Henry Bertoni (Professor Emeritus and Director WICAT, Polytechnic University), in an interview with author, Brooklyn, NY, February 28, 2008. Equation, diagram, and explanation provided by Dr. Bertoni as original work for use in thesis.

$$d_{LC} = \sqrt{wR_c} \quad (3)$$

For curvature in the vertical plane replace w by h in expression (3).

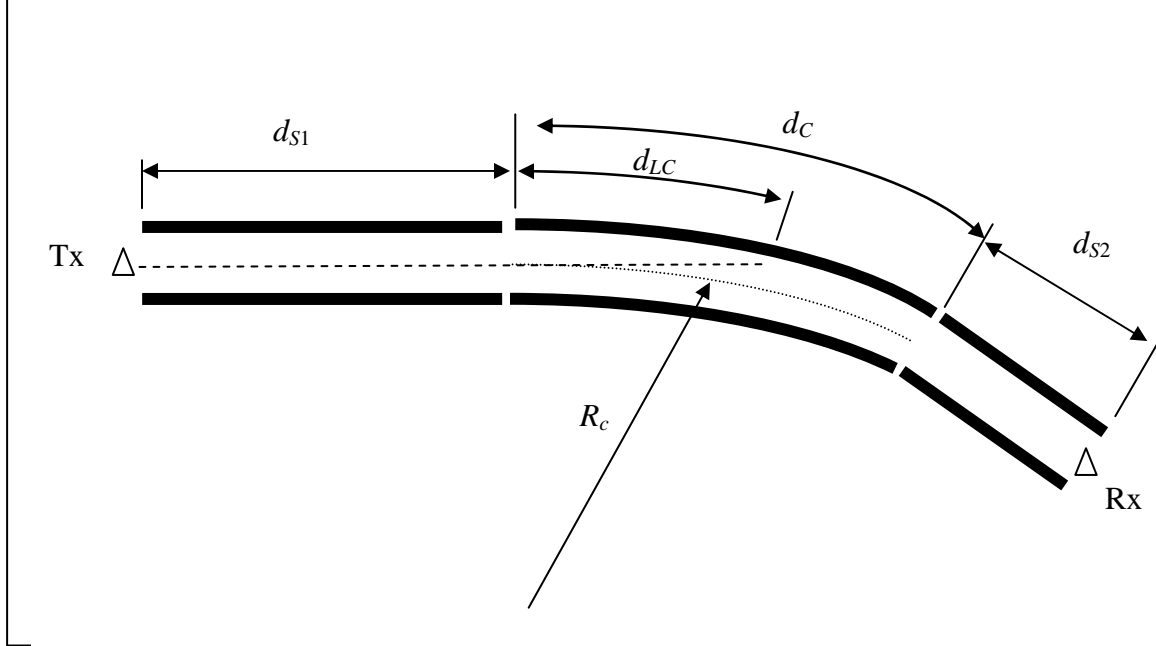


Figure 50. Curved Tunnel Path Loss

With the value (3) of d_{LC} and the lengths d_{s1} and d_{s2} of the straight portions of the tunnel, we define the LOS distance d_{LOS} into the tunnel as the greater of the two values $d_{s1} + d_{LC}$ and $d_{s2} + d_{LC}$. Also, let d be the total distance defined by $d = d_{s1} + d_c + d_{s2}$. Then for distances in the curved portion of the tunnel that are beyond LOS, the path loss in dB between isotropic antennas is

$$PG_{dB} = \begin{cases} 10 \log \left(\frac{\lambda}{4\pi d_{LOS}} \right)^2 + \alpha_{dB}(d - d_{LOS}) + \alpha_c d_c & \text{for } d_{LOS} < x_F \\ 10 \log \left(\frac{\lambda}{4\pi x_F} \right)^2 + \alpha_{dB}(d - x_F) + \alpha_c d_c & \text{for } d_{LOS} \geq x_F \end{cases} \quad (4)$$

In (4) α_c is the additional attenuation with units of dB/m due to curvature of the tunnel.

Values of α_c are given in the technical literature based on theory and measurements for different frequencies, radius of curvature and polarization. An approximate formula for α_c is given below in terms of a constant A whose value is found by fitting to the various reported values.

$$\alpha_c = A \left(\frac{10}{w} \right) \left(\frac{\lambda}{R_c / 1000} \right) \quad (5)$$

In (5) R_c is the radius of curvature of the tunnel. This expression has dependence on R_c that is consistent with M. Nilson, et al and with D.G. Dudley, et al, and frequency dependence that is consistent with D.G. Dudley et al. It further has the property that the attenuation per radian of tunnel bend is the same for all tunnels having the same radius and width when measured in wavelengths, i.e., it scales correctly with frequency. For a horizontally-bending tunnel with vertical polarization, the results of M. Nilson can be fit with the value $A = 0.082$, where as those of D.G. Dudley et al give $A = 0.012$.

Urban canyon¹³⁷

Formulas for urban canyon path gain.

Propagation along a Straight Street

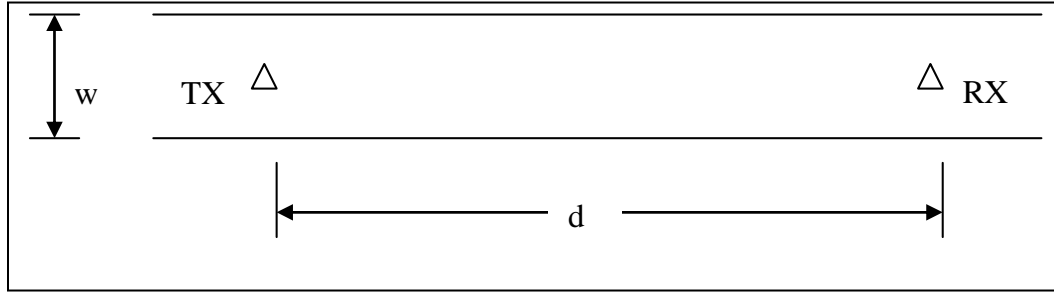


Figure 51. Top View of Street Canyon

Path gain between Transmitter and Receiver:

$$PG \equiv \frac{P_{Rec}}{P_{Tran}} = P_{2R}(d) \begin{cases} e^{-\alpha(d-x_F)} & \text{for } d \geq x_F \\ 1 & \text{for } d < x_F \end{cases} \quad (1)$$

where

$$P_{2R}(d) = \left(\frac{\lambda}{4\pi d} \right)^2 \left[2 \sin \left(\frac{2\pi h_T h_R}{\lambda d} \right) \right]^2$$

$$x_F = \frac{w^2}{\lambda} \quad (2)$$

$$\alpha = \frac{\lambda^2}{w^3 \sqrt{\epsilon_w - 1}}$$

¹³⁷ Henry Bertoni (Professor Emeritus and Director WICAT, Polytechnic University), in an interview with author, Brooklyn, NY, February 28, 2008. Equation, diagram, and explanation provided by Dr. Bertoni as original work for use in thesis.

Propagation Down an Urban Canyon Street and into a Junction

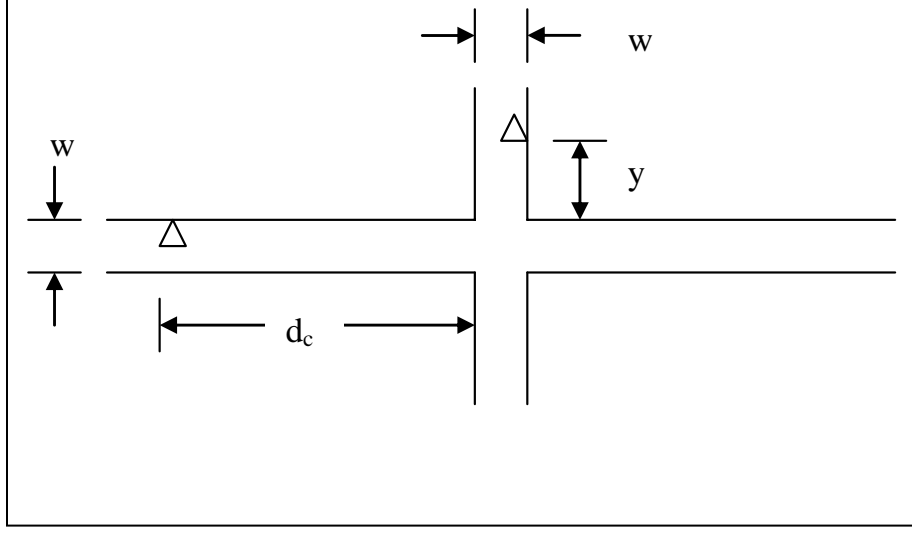


Figure 52. Top View of an Urban Canyon with a Turn onto a Side Street

Path gain between Transmitter and Receiver:

$$PG = P_{2R}(d_c + y)P_{Dif}(y)E(d_c - x_F)E(y - x_F) \quad (3)$$

where $P_{2R}(d_c + y)$ is a given in (2) with (x) replaced by $(d_c + y)$. Also for four diffracting corners

$$P_{Dif}(d_c, y) = 4 \left| D(\phi, \phi') \right|^2 \frac{1}{d_c(y + w/2)} \quad (4)$$

and the two functions $E(u)$ are defined by

$$E(u) = \begin{cases} 1 & \text{for } u < 0 \\ e^{-\alpha u} & \text{for } u \geq 0 \end{cases} \quad (5)$$

In (4) the diffraction function is found using the conducting edge with $\phi' = \pi/2$ and $\phi = \pi$ for TE polarization, i.e. for diffraction for the lower right corner in the figure. In this case

$$D(\pi, \pi/2) = \frac{-\sqrt{\lambda}}{\pi\sqrt{2}} = -0.226\sqrt{\lambda} \quad (6)$$

APPENDIX B.

A. BUILDING WALL LOSS

Wall Loss Measured by Various Means			
Wall Type	Frequency	Reflection Loss	Transmission Loss
Exterior wood frame wall with metal siding	800 MHz 5 - 6 GHz 5 GHz		4 - 7 dB 9 - 18 dB 36 dB
Brick, exterior	4 - 6 GHz	10 dB	14 dB
Concrete block, interior	2.4 / 5 GHz		5 / 5 - 10 dB
Gypsum board, interior	2.4 / 5 GHz		3 / 5 dB
Wooden floors	5 GHz		9 dB
Concrete floors	900 MHz		13 dB

Figure 53. Wall Path Loss ¹³⁸

¹³⁸ Figure 53 from Bertoni, *EL 675 UHF Propagation for Modern Wireless Systems*, Chapter 3, Slide 47.

B. BUILDING PENETRATION

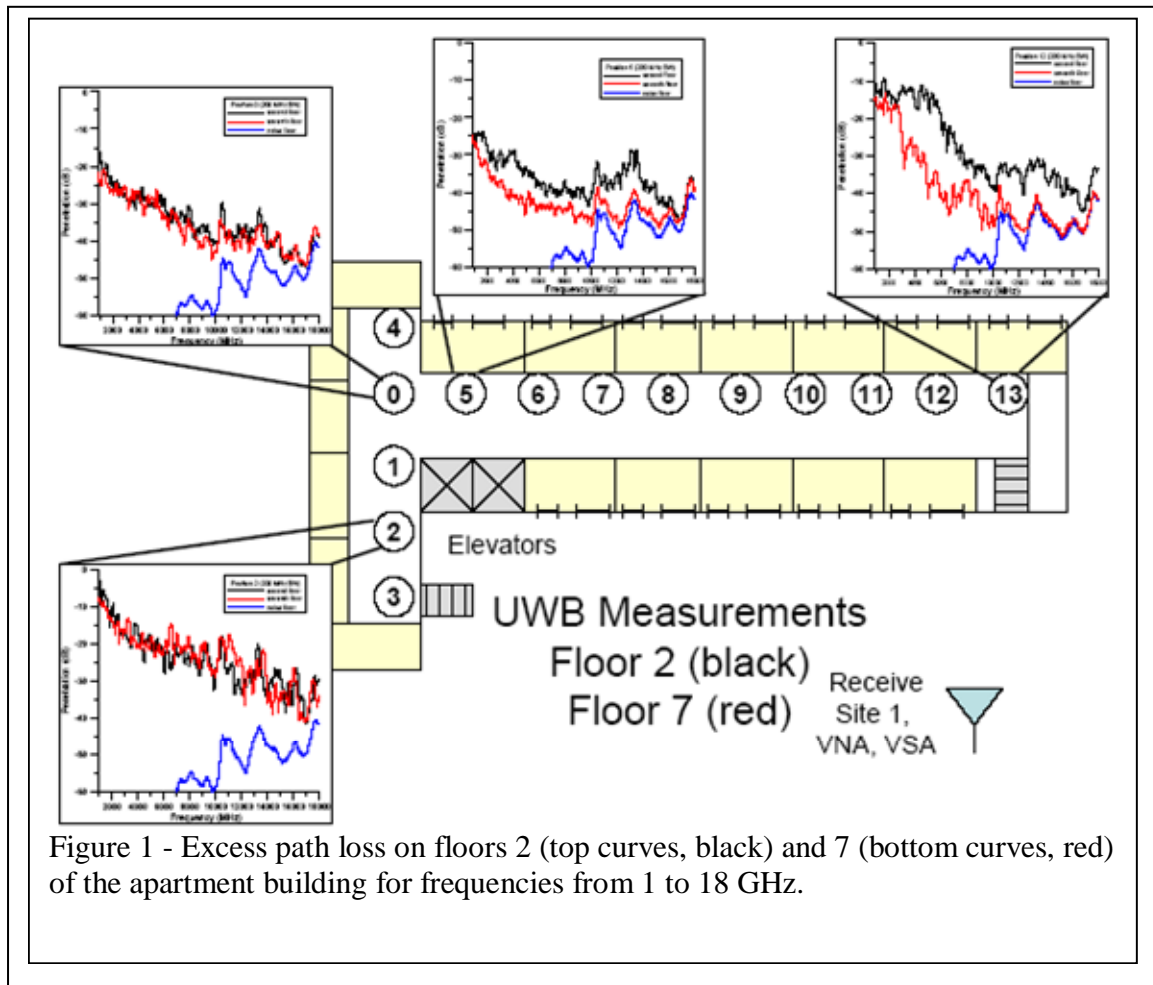


Figure 54. Building Penetration Loss ¹³⁹

¹³⁹ Figure 54 from Remley, "Measurements to Support Modulated-Signal Radio Transmissions," 94.

APPENDIX C

Multi Radio Coexistence Protocol

In an interesting approach to allowing multiple radios to operate in proximity to each other - Multi Radio Coexistence Protocol – Zhu and others point to the benefit of bringing coexistence (multiple types of radio transmissions) awareness into the design of air-interface and wireless protocols, with their simulation results showing up to a 50% performance improvement using their proposed solution. Their approach is based on utilizing a “Media Independent Co-Existence (MICE) Service Layer” that would gather information about the PHY and MAC characteristics of each device, guide radio control through “scheduling multiple radios in frequency, power, and time,” and provide priority and policy guidance when collisions occur.¹⁴⁰ Figure 55 from the paper provides a more thorough explanation.

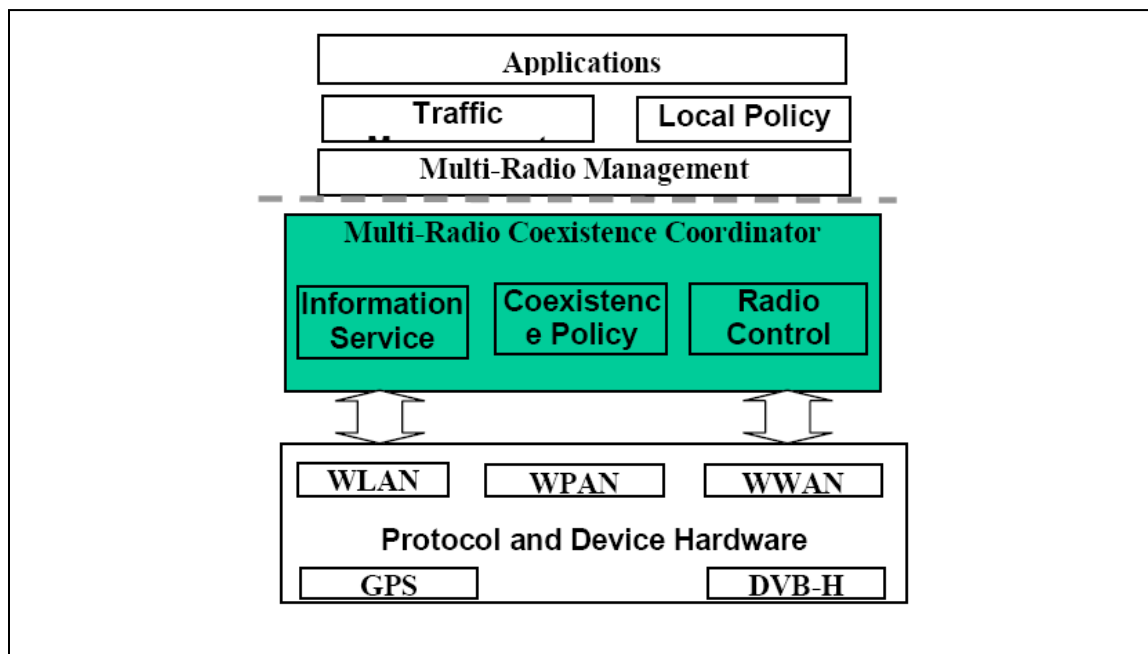


Figure 55. Media Independent Co Existence (MICE) Service Layer¹⁴¹

¹⁴⁰ Remley, “Measurements to Support Modulated-Signal Radio Transmissions,” 94.

¹⁴¹ Figure 55 from Ibid., Figure 5, 362.

Figure 55 shows the authors' future concept for a multi-radio system with a media-independent coexistence service (MICE) layer that includes components such as:

- *Information Service:* to gather necessary information for coexistence interference analysis and guiding radio control, including time scheduling for transmission and spectrum or energy profiles.
- *Radio Control:* to provide commands for coexistence interference mitigation techniques such as scheduling multiple radios in frequency, power, and time.
- *Coexistence Policy:* to provide priority and policy when collision or conflict occurs among radios with the ability to adapt to coexistence interference.¹⁴²

¹⁴² Remley, "Measurements to Support Modulated-Signal Radio Transmissions," 363.

LIST OF REFERENCES

- Andrews, J. G., S. Weber, and M. Haenggi. "Ad Hoc Networks: To Spread Or Not to Spread? [Ad Hoc and Sensor Networks]." *IEEE Communications Magazine* 45, no. 12 (December 2007): 84-91.
- BAA 07-46 LANdroids Broad Agency Announcement (BAA) for Information Processing Technology Office (IPTO) Defense Advanced Research Projects Agency (DARPA). Washington, DC: Defense Advanced Research Projects Agency (DARPA), 2007, http://www.darpa.mil/ipto/solicit/open/BAA-07-46_PIP.pdf (accessed February 7, 2008).
- Bacon, David and Nick Thomas. "Simulation and Modelling of Propagation Paths Involving the Indoor/Outdoor Interface." In *Proceedings of the International Symposium on Advanced Radio Technologies*. Boulder, CO: 2007.
- Bedford, Brent and Frank Sanders. "Spectrum Sharing and Potential Interference to Radars." In *Proceedings of the International Symposium on Advanced Radio Technologies*. 72-77. NTIA Special Publication SP-07-445. Washington, DC: Department of Commerce, National Telecommunications and Information Administration, 2007.
- Bertoni, Henry. *Lecture Slides for EL 675 - UHF Propagation for Modern Wireless Systems*. Brooklyn, NY: Polytechnic University, Department of Electrical Engineering, 2005?, <http://eeweb.poly.edu/faculty/bertoni/el675.html> (accessed March 4, 2008).
- Bertoni, Henry L. *Radio Propagation for Modern Wireless Systems*. Upper Saddle, NJ: Prentice Hall Professional Technical Reference, 2000.
- Blackburn, Michael R., H. R. Everett, and Robin T. Laird. *After Action Report to the Unmanned Ground Vehicles/Systems-Joint Program Office: Center for the Robotic Assisted Search and Rescue (CRASAR) Related Efforts at the World Trade Center*. San Diego, CA: SSC San Diego, 2002, <http://handle.dtic.mil/100.2/ADA407901> (accessed March 1, 2008).

- Blitch, John. "Semi-Autonomous Tactical Robots for Urban Operations." In *Proceedings of the 1998 IEEE ISIC/CIRA/ISAS Joint Conference*, 783-794. Gaithersburg, MD: September 14-17, 1998.
- "Bombers Target London." <http://www.cnn.com/SPECIALS/2005/london.bombing/> (accessed March 4, 2008).
- "Building a Better Bomb Robot." *TechBeat* (Summer 2004): 1-2, <http://www.nlectc.org/techbeat/summer2004/04-Building%20A%20Robot.pdf> (accessed June 2, 2007).
- Bullington, K. "Radio Propagation at Frequencies Above 30 Megacycles." *Proceedings of the IRE* 35, no. 10 (October, 1947): 1122-1136.
- Casper, Jennifer and Robin R. Murphy. "Human-Robot Interactions during the Robot-Assisted Urban Search and Rescue Response at the World Trade Center." *IEEE Transactions on Systems, Man, and Cybernetics, Part B, Cybernetics* 33, no. 3 (June 2003): 367-385.
- Chan, Sewell. "Who's Watching the Underwater Tunnels." *New York Times*, July 20, 2005, <http://www.nytimes.com/2005/07/20/nyregion/20tunnels.html?n=Top/Reference/Times%20Topics/People/F/Fahim,%20Kareem> (accessed March 4, 2008).
- Colvin, Caran and Angeline Goh. "Validation of the Technology Acceptance Model for Police." *Journal of Criminal Justice* 33, no. 1 (January/February 2005): 89-95.
- Comeau, Ed and Bill Flynn. "The Big: NFPA 502 Drives Safety of the World's Biggest Tunnel System." *NFPA Online Journal* (May/June 2003), <http://www.nfpa.org/archivedJournalHOME.asp?categoryID=690&src=NFPAJournal> (accessed March 4, 2008).
- Davidson, A. and C. Hill. "Measurement of Building Penetration into Medium Buildings at 900 and 1500 MHz." *IEEE Transactions on Vehicular Technology* 46, no. 1 (February, 1997): 161-168.

- Davis, Fred D., Richard P. Bagozzi, and Paul R. Warshaw. "User Acceptance of Computer Technology: A Comparison of Two Theoretical Models." *Management Science* 35, no. 8 (August 1989): 982-1003.
- Dougherty, Jill. "Moscow Metro Blast Kills 39." *Cnn.Com*, February 6, 2004, <http://www.cnn.com/2004/WORLD/europe/02/06/moscow.blast/> (accessed March 20, 2008).
- Dudley, D. G., M. Lienard, S. F. Mahmoud, and P. Degauque. "Wireless Propagation in Tunnels." *IEEE Antennas and Propagation Magazine* 49, no. 2 (April 2007): 11-26.
- Erceg, Vinko, A. J. Rustako Jr., and R. S. Roman. "Diffraction Around Corners and its Effects on the Microcell Coverage Area in Urban and Suburban Environments at 900 MHz, 2 GHz, and 6 GHz." In *Proceedings of the IEEE Global Telecommunications Conference, GLOBECOM '94.*, edited by A. J. Rustako Jr. Vol. 1, 52-57. San Francisco, CA: 1994.
- Flickenger, Rob, Corinna Aichele, Sebastian Büttrich, and Laura M. Drewett. *Wireless Networking in the Developing World: A Practical Guide to Planning and Building Low-Cost Telecommunications Infrastructure*. 2nd ed. Hacker Friendly, LLC, 2007, <http://wndw.net/download.html#english> (accessed March 4, 2008).
- Fruchtman, Steve, et al. *IAFF Training for Hazardous Materials: Technician Instructor Guide, Module 10: Incident Management*. Washington, DC: International Association of Firefighters, 2002.
- Fuxjäger, Paul, Danilo Valerio, and Fabio Ricciato. "The Myth of Non-Overlapping Channels: Interference Measurements in IEEE 802.11." In *Fourth Annual Conference on Wireless on Demand Network Systems and Services, 2007. WONS '07*, 1-8. Obergurgl Tyrol, Austria: January 24-26, 2007, <http://www.dps.uibk.ac.at/wons/program/WONS2007-fuxjaeger.pdf> (accessed March 9, 2008).
- Gardner, W. David. "Congressional Hearings Planned on FCC 700-MHz Auction." *InformationWeek*, March 21, 2008, <http://www.informationweek.com/news/showArticle.jhtml?articleID=206905201> (accessed March 21, 2008).

- Harper, F. T., S. V. Musolino, and W. B. Wente. "Realistic Radiological Dispersal Device Hazard Boundaries and Ramifications for Early Consequence Management Decisions." *Health Physics* 93, no. 1 (July 2007): 1-16.
- Hofmann, Philipp, et al. "Are IEEE 802 Wireless Technologies Suited for Firefighters?" In *12th European Wireless Conference - "Enabling Technology for Wireless Multimedia Communications."* Athens, Greece: April 2-5, 2006, <http://www.bettstetter.com/publications/hofmann-2006-ew-fire.pdf> (accessed June 2, 2007).
- Holloway, Christopher L., et al. "Radio Propagation Measurements during a Building Collapse: Applications for First Responders." In *Proceedings of the International Symposium on Advanced Radio Technology, ISART 2005*, 61-63. Boulder, CO: March 2005, http://www.boulder.nist.gov/div818/81802/MetrologyForWirelessSys/pubs/R3_ISART05_Holloway_com.pdf (accessed March 20, 2008).
- Hoppe, R., G. Wolfle, and F. M. Landstorfer. "Measurement of Building Penetration Loss and Propagation Models for Radio Transmission into Buildings." In *IEEE VTS 50th Vehicular Technology Conference, 1999*. Vol. 4, 2298-2302. Amsterdam: September 19-22, 1999.
- "iRobot Wins \$286 Million Dollar Army Contract." *HSDailyWire.Com*, December 19, 2007, <http://hsdailywire.com/single.php?id=5258> (accessed March 1, 2008).
- Jackson, Brian A., et al. *Protecting Emergency Responders: Volume 3: Safety Management in Disaster and Terrorism Response*. Washington, DC: Science and Technology Policy Institute (RAND) and the National Institute for Occupational Safety and Health, 2004, http://www.rand.org/pubs/monographs/2004/RAND_MG170.pdf (accessed June 2, 2007).
- Joe, Leland and Isaac Porche III. *Future Army Bandwidth Needs and Capabilities*. Santa Monica, CA: Rand, Arroyo Center, 2004, http://www.rand.org/pubs/monographs/2004/RAND_MG156.pdf (accessed June 2, 2007).

- Kleiner, Alexander and Christian Dornhege. "Real-Time Localization and Elevation Mapping Within Urban Search and Rescue Scenarios." *Journal of Field Robotics* 24, no. 8-9 (August-September 2007): 723-745.
- Kristof, Nicholas D. "Mysterious Fumes in Japan Store Send 24 to Hospitals." *New York Times*, April 21, 1995.
- "Leaders Condemn India Train Blast." *BBC News*, February 19, 2007, http://news.bbc.co.uk/2/hi/south_asia/6375749.stm (accessed March 4, 2008).
- Lee, Jeho and Henry Bertoni. "Coupling at Cross, T, and L Junctions in Tunnels and Urban Street Canyons." *IEEE Transactions on Antennas and Propagation* 51, no. 5 (May 2003): 926-935.
- Lundberg, Carl. "Assessment and Evaluation of Man-Portable Robots for High-Risk Professions in Urban Settings." PhD, Stockholm University, 2007, <http://www.diva-portal.org/kth/theses/abstract.xsql?dbid=4540> (accessed February 9, 2008).
- Lundberg, Carl, Henrik Christensen, and Roger Reinhold. "Long-Term Study of a Portable Field Robot in Urban Terrain." *Journal of Field Robotics* 24, no. 8-9 (August 2007): 625-650.
- McHale, John. "Robots are Fearless." *Military & Aerospace Electronics* (June, 2006): March 1, 2008, http://mae.pennnet.com/display_article/258264/32/ARTCL/none/none/1/Robots-are-fearless/ (accessed March 1, 2008).
- McHenry, Mark A., Peter A. Tenhula, and Dan McCloskey. "Chicago Spectrum Occupancy Measurements & Analysis and a Long-Term Studies Proposal." In *Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum*. TAPAS '06 ed. Vol. 222. Boston, MA: ACM, August 2-5, 2006.

- MESA TS 70.001 v.3.1.2 (2005-01) *Technical Specification: Project MESA; Service Specification Group - Services and Applications; Statement of Requirements*. Valbonne, France: MESA Organizational Partners (ETSI, TIA), 2005, http://www.projectmesa.org/ftp/Specifications/MESA_70.001_V3.1.2_SoR.doc (accessed February 9, 2008).
- Messina, Elena, et al. *Statement of Requirements for Urban Search and Rescue Robot Performance Standards: Preliminary Report*. Washington, DC: National Institute of Standards and Technology, 2005, [http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements%20Report%20\(prelim\).pdf](http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements%20Report%20(prelim).pdf) (accessed June 12, 2007).
- Murphy, Robin R. "Rats, Robots, and Rescue." *IEEE Intelligence Systems* 17, no. 5 (September/October 2002): 7-9, <http://csdl2.computer.org/persagen/DLAbsToc.jsp?resourcePath=/dl/mags/ex/&to c=comp/mags/ex/2002/05/x5toc.xml&DOI=10.1109/MIS.2002.1039826> (accessed June 2, 2007).
- Murphy, Robin R. "Trial by Fire." *IEEE Robotics and Automation Magazine* 11, no. 3 (September 2004): 50-61.
- Musolino, Stephen V. and Frederick T. Harper. "Emergency Response Guidance for the First 48 Hours After the Outdoor Detonation of an Explosive Radiological Dispersal Device." *Health Physics* 90, no. 4 (April 2006): 377-385.
- NASA Center for Aerospace Information. "All-Terrain Intelligent Robot Braves Battlefield to Save Lives." NASA. http://www.sti.nasa.gov/tto/Spinoff2005/ps_1.html (accessed June 2, 2007).
- "Noblis Awarded \$1.8 Million Cooperative Agreement for Security, Video-Quality Research." Noblis, Inc. http://www.noblis.org/NewsReleases_4192.asp (accessed March 9, 2008).
- Noll, Gregory G., Michael S. Hildebrand, and James G. Yvorra. *Hazardous Materials: Managing the Incident*. 2nd ed. Stillwater, OK: Fire Protection Publications, 1995.

- "Oversight: MTA and NYC Subway System Emergency Evacuation Plans, Protocols, and Procedures." Governmental Affairs Division, Transportation Council, New York City. <http://webdocs.nycouncil.info/attachments/76003.htm> (accessed March 4, 2008).
- Pezeshkian, Narek, Hoa G. Nguyen, and Aaron Burmeister. "Unmanned Ground Vehicle Non-Line-of-Sight Operations using Relaying Radios." In *Proceedings of the 12th IASTED International Conference Robotics & Applications*. Honolulu, HI: August 14-16, 2006, http://www.spawar.navy.mil/robots/pubs/IASTED_ADCR.pdf (accessed June 2, 2007).
- Pinson, Margaret H., Stephen Wolf, and Robert B. Stafford. "Video Performance Requirements for Tactical Video Applications." In *2007 IEEE Conference on Technologies for Homeland Security*, 85-90. Woburn, MA: May 16-17, 2007.
- Public Safety Wireless Network Program. *In Building/In Tunnel User Considerations: Final*. Washington, DC: PSWN Program, 2002, http://www.safecomprogram.gov/NR/rdonlyres/C45C80A6-9D3D-4A61-8E8C-B30FB71CE850/0/In_Building_In_Tunnel_User_Considerations.pdf (accessed March 4, 2008).
- Rak, Milan and Pavel Pechac. "UHF Propagation in Caves and Subterranean Galleries." *IEEE Transactions on Antennas and Propagation* 55, no. 4 (April 2007): 1134-1138.
- Rashbaum, William K. and William Neuman. "PATH Tunnels seen as Fragile in Bomb Attack." *New York Times*, December 22, 2006, http://www.nytimes.com/2006/12/22/nyregion/22security.html?_r=1&th&emc=th&oref=slogin (accessed March 4, 2008).
- Remley, Kate A. and et al. *Measurements to Support Modulated-Signal Radio Transmissions for the Public-Safety Sector*. Washington, DC: U.S. Department of Commerce, NIST Electromagnetics Division, 2007.

- Remley, Kate A., Galen Koepke, Elena Messina, Adam Jacoff, and George Hough. "Standards Development for Wireless Communications for Urban Search and Rescue Robots." In *Proceedings of the International Symposium on Advanced Radio Technologies, February 26-28, 2007*. NTIA Special Publication SP-07-445, 66-70. Washington, DC: National Telecommunications and Information Administration, 2007, http://www.its.bldrdoc.gov/pub/ntia-rpt/07-445/report_07-445.pdf (accessed March 2, 2007).
- . "Standards Development for Wireless Communications for Urban Search and Rescue Robots." In *Proceedings of the International Symposium on Advanced Radio Technologies*. Boulder, CO: 2007, http://www.nist.gov/public_affairs/techbeat/NISTRobotCommStds1.pdf (accessed March 4, 2007).
- "Robots in Tunnels: A New Environment for Technology that Works." Transportation Security Administration. http://www.tsa.gov/press/happenings/robots_in_tunnel.shtml (accessed March 4, 2008).
- Rose, David M. *Public Transportation Security: Volume 3 - Robotic Devices: A Guide for the Transit Environment*. Washington, DC: Transportation Research Board, Transit Cooperative Research Program, 2003, http://trb.org/publications/tcrp/tcrp_rpt_86-v3.pdf (accessed March 26, 2008).
- Shiroma, Naoji, Noritaka Sato, Yu-huan Chiu, and Fumitoshi Matsuno. "Study on Effective Camera Images for Mobile Robot Teleoperation." In *13th IEEE International Workshop on Robot and Human Interactive Communication, 2004. ROMAN 2004.*, 107-112. Kurashiki, Okayama Japan: 20-22 September 2004.
- "Signal to Noise Ratio." RAD University. <http://www2.rad.com/networks/2006/db/snr.htm> (accessed March 4, 2008).
- Souryal, Michael R., Johannes Geissbuehler, Leonard E. Miller, and Nader Moayeri. "Real-Time Deployment of Multihop Relays for Range Extension." In *Proceedings of the 5th International Conference on Mobile Systems, Applications and Services*, 85-98. San Juan, Puerto Rico: 2007, http://www.usenix.org/events/mobisys07/full_papers/p85.pdf (accessed March 26, 2008).

- Sridhara, Vinay and Stephan Bohacek. "Realistic Propagation Simulation of Urban Mesh Networks." *Computer Network* 51, no. 12 (August, 2007): 3392-3412, <http://dx.doi.org/10.1016/j.comnet.2007.01.035> (accessed March 4, 2008).
- TriData. *The Economic Consequences of Firefighter Injuries and Their Prevention. Final Report*. Arlington, VA: TriData for National Institute of Standards and Technology, 2005, http://www.fire.gov/newsletter/winter2005/Tridata/EcCostFFInj_GCR%2005_874.pdf (accessed June 2, 2007).
- U.S. Department of Homeland Security. *National Preparedness Guidelines*. Washington, DC: US Department of Homeland Security, 2007, <https://www.hsdl.org/homesec/docs/dhs/nps23-091407-01.pdf&code=d3fb737cee88df0f3c62d3d65e80f479> (accessed March 1, 2008).
- U.S. Department of Homeland Security, SAFECOM Program. *Public Safety Statement of Requirements for Communications and Interoperability. Volume II, Version 1.0*. Washington, DC: SAFECOM Program, 2006, http://www.safecomprogram.gov/NR/rdonlyres/B20DC842-B760-4DB0-B3B6-D3F1B0A5F26B/0/PS_SoR2_v10_9112006.pdf (accessed March 4, 2008).
- U.S. Department of Transportation. *Emergency Response Guidebook: Flammable Liquids (Non-Polar/Water-Immiscible). Guide 128*. Washington, DC: Department of Transportation, Pipeline and Hazardous Materials Safety Administration, 2004, <http://hazmat.dot.gov/pubs/erg/g128.pdf> (accessed March 9, 2008).
- U.S. Fire Administration. *The World Trade Center Bombing: Report and Analysis: New York City, New York*. Washington, DC: Department of Homeland Security, 2003, <http://www.usfa.dhs.gov/downloads/pdf/publications/tr-076.pdf> (accessed March 10, 2008).
- U.S. National Institute of Occupational Safety and Health. *Current Status, Knowledge Gaps, and Research Needs Pertaining to Firefighter Radio Communication Systems*. Washington, DC: NIOSH, 2003, <http://www.cdc.gov/niosh/fire/pdfs/FFRCS.pdf> (accessed June 2, 2007).

- Welch, R. V. and G. O. Edmonds. *Requirements for Robots Utilized at HAZMAT Incident Sites*. Huntsville, Alabama: AIAA, 1994, <http://hdl.handle.net/2014/33146> (accessed March 1, 2008).
- "What can Project MESA do for Public Protection, Public Safety, National Defense Organizations, and the Citizens they Serve." (accessed March 4, 2008).
- Winso, James H., et al. "Geometrically Optimized, Labr3:Ce Scintillation Sensor Array for Enhanced Stand-Off Direction Finding of Gamma Radiation Sources." In *2007 Nuclear Science Symposium and Medical Imaging Conference*. Honolulu, HI: October 27-November 3, 2007, http://www.spawar.navy.mil/robots/pubs/NSS_07.pdf (accessed March 11, 2008).
- Wong, James, et al. *Urban Search and Rescue Technology Needs: Identification of Needs*. Washington, DC: US Department of Homeland Security and FEMA, 2004, <http://www.ncjrs.org/pdffiles1/nij/grants/207771.pdf> (accessed March 7, 2008).
- Zhu, Jing, Alan Waltho, Xingang Guo, and Xue Yang. "Multi-Radio Coexistence: Challenges and Opportunities." In *Proceedings of 16th International Conference on Computer Communications and Networks, 2007. ICCCN 2007*. 358-364. Honolulu. HI: August 13-16, 2007.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California
3. Nicholas Scoppetta – Fire Commissioner
Fire Department of New York City
Brooklyn, New York
4. Frank Cruthers – First Deputy Commissioner
Fire Department of New York City
Brooklyn, New York
5. Salvatore Cassano – Chief of Department
Fire Department of New York City
Brooklyn, New York
6. Patrick McNally – Chief of Operations
Fire Department of New York City
Brooklyn, New York
7. Michael Weinlein – Manhattan Borough Commander
Fire Department of New York City
Brooklyn, New York
8. Joseph W. Pfeifer – Chief of Counterterrorism and Emergency Preparedness
Fire Department of New York City
Brooklyn, New York